

## UNITED STATES AIR FORCE RESEARCH LABORATORY

### THE HUMAN-ELECTRONIC CREW: THE RIGHT STUFF?

Proceedings of the 4th Joint GAF/RAF/USAF  
Workshop on Human-Computer Teamwork

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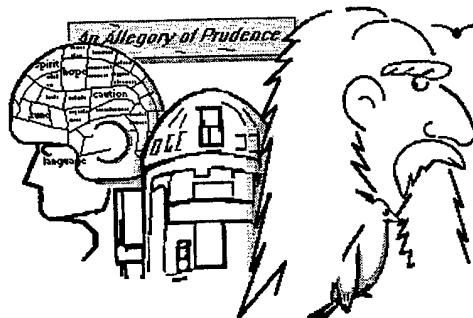
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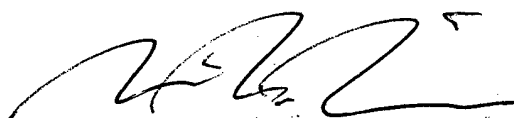
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**FOR THE COMMANDER**



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## OBJECTIVE

The components integral to the operation of an Electronic Crewmember have started to take shape. Questions have been raised as to the nature of the EC when finished. What are the key components that will ensure a successful emergence of this new technology? How can we plan for their development and incorporate the software and hardware elements to function in concert with one another. The purpose of this workshop was to examine these concerns.

This meeting was a follow up to previously successful meetings (1988, 1990 and 1994) co-sponsored by the German Air Force, Royal Air Force, and the US Air Force Wright Laboratory and European Office of Aerospace Research and Development. This fourth meeting provided a valuable forum for the experts of several countries to measure progress in this critical technical area. It also allowed for the exchange of new ideas, concepts, and data relative to hardware and software capabilities that can be included in an aircraft system design, to aid the human operator to perform the mission. *Attendance at this workshop was by invitation only.* It brought together experts representing cockpit design disciplines including hardware and software technologists, as well as human factors specialists, and pilots to wrestle with questions such as:

- (1) What are the core qualities that the Electronic Crewmember must possess?
- (2) How does one estimate the amount of software code involved?
- (3) What are the key software modules?
- (4) What is necessary to ensure the modules function symbiotically?
- (5) What is sufficient functionality within the Electronic Crewmember to satisfy the human operator requirements?

The workshop comprised formal paper sessions and small group discussions. Proceedings will be published in reports by the sponsoring laboratories. *The numbers of persons attending was restricted to 60.* All invited attendees were expected to contribute through formal presentations or through active participation in the meeting discussions. The selection of invitees was based on the quality of the proposed contributions. An attempt was made to balance representation across nations as well as across themes.

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## WORKSHOP BACKGROUND

Ever since the movie *Star Wars* showed Luke Skywalker and R2D2 teaming up to destroy the Death Star, there has been considerable speculation as to how an efficient pilot-robot team could be created. Since weight is a critical design factor in airborne systems, the literal building of a pilot-robot team has not been undertaken; rather, the emphasis shifted to incorporating the intelligence of the robot. As work in this area progressed, such terms as "electronic crewmember" and "black box back seater" began to enter the vocabulary of both the crewstation design and computer software communities. While the use of these titles served to stimulate thinking in the area of human-computer teamwork, a major program was required to start the design and implementation of concepts needed to build an electronic crewmember (EC); in the US this took the form of the Pilot's Associate (PA) Program. The establishment of the PA Program in 1985 gave credence to the idea that the building of the brain of R2D2, in some very simplified form, might be possible. The some of the results of this program have been transitioned to the US Army's Rotary Pilot's Associate Program which continues to strive for the same goal. In Europe, AI efforts have centered around a number of programs. These include the French "Co-pilote Electronique", the British Mission Management Aid (MMA), and the German Crew Assistant Military Aircraft (CAMA) Cockpit Assistant Systems. They too have tried to achieve the goal of human computer teamwork in the cockpit.

In the next two years, numerous discussions were held to explore some of cockpit ramifications created by the use of a pilot-EC team within the aircraft. These discussions occurred in various technical meetings within the US and the UK. In one of the meetings held in the US, attended by representatives of the Air Force of the then Federal Republic of Germany (FRG), as well as US and UK representatives, the idea of the initial workshop was born. Although progress on the idea of a workshop concerning human-EC teamwork continued, in 1987 an event occurred which demonstrated the definite need for the workshop.

In April of 1987, USAF representatives gave a paper at a meeting of the Royal Aeronautical Society in London and again at a meeting of the Ergonomics Society in Swansea, Wales. The subject of the paper was "Workload and Situation Awareness in Future Aircraft", and a section of the paper discussed workload sharing between the pilot and the EC. During both meetings the same kinds of questions were asked: Is the pilot always in charge? Can the pilot and EC really be called a team? Why do you need the pilot at all?

These thought provoking questions resulted in continued discussions with technical personnel in the US, UK and FRG, and the result was the 1988 workshop entitled, "The Human-Electronic Crew: Can They Work Together". The workshop was documented by the Royal Air Force (RAF IAM BSD-DR-G4, Dec 1988, and the U.S. Air Force WRDC-TR-89-7008, Jul 1989). Following the 1988 workshop, interest was expressed in holding an additional meeting on the topic of human-electronic teamwork. The result was a 1990 workshop entitled, "The Human-Electronic Crew: Is the Team Maturing", (RAF IAM PD-DR-P5, April 1991; WL-TR-92-3078, July 1992). The 1988 and 1990 workshops were sponsored by the USAF European Office of Aerospace Research and Development (EOARD), and hosted very generously by the German Air Force.

There was a four year hiatus between the second and third workshops. Events relating to end of the Cold War caused a very dynamic environment, with many governmental reorganizations occurring on both sides of the Atlantic. After these events were sorted out, plans began to convene the third workshop. Sponsorship was obtained from EOARD, and resulted in the third workshop, which the Royal Air Force hosted in Cambridge, England., "The Human-Electronic Crew: Can We Trust the Team? (DRA/CHS/HS3/TR95001/01, Jan 1995; WL-TR-96-3039, Dec 1995).

The fourth of the workshop series, which is described in these proceedings, was again sponsored by EOARD and was held in Kreuth, Germany in 1997. The theme of this conference was "The Human Electronic-Crew: the Right Stuff?", and the German Air Force, Universitat der Bundeswehr, graciously served as host.

## EXECUTIVE SUMMARY

The meeting was divided into two sections: formal presentations (papers) and workshop. The 29 papers, presented by representatives from seven different countries, fit into four major categories: mission descriptions, design methodology, human-electronic crew interface technologies, and the use of an EC in the commercial aircraft arena. A summary of the ideas from the papers is given below.

### Papers

The papers covered how to communicate with the electronic crewmember through automatic speech recognition, and also discussed display formats in order to show the output of the EC. Applications were shown in both an airborne and naval environments. Detailed applications, which presented two decision aids in great detail, were demonstrated in a French discussion of *The Copilote Electronique* and a German presentation on *The Crew Assistant Military Aircraft (CAMA)*.

The topic of the application of the EC to commercial aircraft was also discussed in detail. The demonstration of one small version of the EC which could be applied in this environment, The Hazard Monitor, showed that the EC does have potential in this area. However, the issue of certification of the EC in the commercial aircraft environment remains a very important concern.

A step forward in the goal of building the Human-Electronic Crewmember team was presented in a series of papers. One dealt with a new way to communicate with the EC using shortcut language called plays (used extensively in American football). Others discussed the functional architecture for constructing the EC, as well as the "cognitive architectures" of the pilot. Both of these features could be crucial in the effort to build a teaming relationship between the EC and the operator.

### Workshop

After the presentation of the papers, the second half of the meeting consisted of a workshop; its purpose was to form five teams to deal with AI technology and cockpit implications of the technology. The teams were composed of three technical disciplines represented at the conference -- aircrew, crewstation designers, and artificial intelligence experts. At the end of the workshop, each of the five team leaders presented the results of their deliberations. The details are documented in the Group Discussions portion of these proceedings; a summary is presented below.

There were two key conclusion which resulted from the workshop committees. The first was that there is definite interest in an EC for commercial aircraft. However, the certification of an EC in the commercial arena may be much more difficult than in the military arena because of safety considerations. The second conclusion was that as conventional avionics become more sophisticated, and more "mini-EC" decision aids come online, many parts of the EC may be created from the bottom up. The key component that may remain in the creation of the EC is the software supervising the activities of the subparts.

## CONCLUSION

Besides the technical information gathered, one of the major accomplishments was the positive interchange among the participants. There was a genuine sharing of information and ideas in order to attack the common problem of information overload in the cockpit. The participating countries are striving to reach a common goal, and the ideas exchanged in the Workshop should prove very beneficial to all of them.

# KEYNOTE ADDRESS

## UK MOD OPERATIONAL REQUIREMENTS

by

Squadron Leader M W G Hopkins MBE MA RAF  
Operational Requirements (Air)  
Ministry of Defence

I should like to thank Reiner Onken, Bob Taylor and John Reising, the Workshop Co-Directors, for inviting me to give the UK MOD perspective and Operational Requirements for the Human-Electronic Crew. I am grateful to the workshop for allowing me to follow in Gp Capt Dusty Miller's footsteps and, hopefully, continue with the line he put forward in his opening address in Cambridge in 1994. As part of the MOD sponsor team for Air Human Factors research, I am particularly pleased that such a workshop should be taking place. In these days of financial restraint in all matters military, and especially research, it is crucial that we should be maximising the talents and resources of our respective nations - we can no longer work in isolation if we are to influence cockpits of the future and, indeed, get them right. As a front-line pilot (and customer) I do not propose to lecture the considerable intellects present on the technological and psychological issues but to try and bring to bear some of my operational experience. It is this kind of input that I believe to be crucial, not only in this area, but throughout military-focused research if we (the military) are to get value for our increasingly limited budget whilst retaining the military effectiveness - in short, the edge.

There is no doubt that, as the information revolution gathers pace, the cockpit, and the command and control aspects, will dominate the design and integration of future aircraft. Gone are the days of engineers designing cockpits on their own - it is now the domain of a team of engineers, human factors specialists and aircrew striving to achieve the optimum balance. I am confident this teaming will and must continue if we are to

satisfy the only non-variable in the equation - the human - although I accept that there is much variation and unpredictability within the species.

Questions I am often asked are: will future combat aircraft have a cockpit and what form will the future inhabited cockpit take?

To answer the first of those questions - I believe the manned combat aircraft is here to stay for some considerable time and the simple reason for this is that rules of engagement will mandate a man-in-the-loop to satisfy the political constraints. Some will argue that this man-in-the-loop function can be achieved remotely but they have yet to prove that totally secure, reliable communications can be achieved world-wide, under hostile conditions, and throughout the 24 hr period. Historically, as there have been major leaps in technology, the rules of engagement have been tightened. Indeed, before the cessation of hostilities in Bosnia, the 3 Star General who ran the air operation from his HQ in Italy would often talk directly to the pilot about the target he was about to be given permission to engage. Some may say this is an isolated example and that we must provision purely for a NATO Regional Conflict. I and most of the military disagree. Since 1990 I have personally flown on operations during the Gulf War, policing IRAQ and providing Close Air Support to the UNPROFOR in Bosnia. None of those operations conform to the Regional Conflict model and throughout the rules of engagement were tightened thanks, primarily, to the media. We the military must maintain the **flexibility** to operate anywhere at any time in any role the

politicians see fit to employ us. Flexibility is a subject to which I will return.

So if you accept that, for the foreseeable future the cockpit will be manned in combat aircraft what form will it take? The answer to that one is simple - I don't know and I leave it to the aerospace companies and research scientists to give me (being the MOD) that knowledge. I do know, however, what I wish that cockpit to achieve and that is that it must allow me, the pilot, to effectively operate that aircraft, throughout the performance envelope, in all declared roles making use of all available information and fully integrated within the C<sup>2</sup> architecture. In addition, I must be able to carry out the intentions of the political leaders, military commanders and, some would argue, myself. A tall order I hear you cry. Let me try and define further.

Should the cockpits have 1 or 2 seats? This could be the subject of a whole workshop in itself and probably a very emotive one. However, I believe that cost alone will dictate that future aircraft will be single-seat. Indeed, we have already gone down that route in Europe with the procurement of Eurofighter and our cousins in the US are committed to single seat with F22 and JSF. There is no doubt that current platforms with complicated systems need a 2 seat crew to enable them to operate effectively and, indeed, the argument for 2 pairs of eyes versus one is well made. Automation will discharge this requirement, providing it also adequately maintains situation awareness, and will also remove the problem of poor crew co-operation, a factor often cited in recent accident reports; the human is often lacking in communicating with his own kind. This leaves only one interface - the single crew member and the avionics - an area on which we in the UK plan to focus more over the next few years. What do I require from that interface? Experience has taught us that giving too much control to a machine can be fatal - the pilot of an A320 attempting a fly-by at an

airshow found that out when the aircraft would not allow him to apply power because he had selected a landing mode. It is widely accepted, although there are still considerable pockets of resistance, that man and the automation must work as a team, particularly whilst that man is responsible for the conduct of the mission. Moreover, if the pilot is to maintain control then he must understand and indeed **trust** his R2D2 - a crucial point. We must avoid an often-uttered comment on flight decks and in front of PCs (particularly mine) - "what's it doing now" - if that teaming is to work.

What level of automation should be off-loaded to the machine and what should rest with the man? This is perhaps the crux of the matter. I believe the answer is that, ideally, it should vary depending on a multitude of factors. Pilots are often quoted as saying that when the gear comes up they lose 50% of their brain capacity and that when they come under fire the other 50% deserts them. I remember experiencing something along those lines on Day 1 of the Gulf War in my Jaguar, an aircraft not noted for its automation. However, by Day 10 the experience of the previous missions had been assimilated and my spare capacity had improved immeasurably. I would have been enormously grateful if, on Day 1 automation could have off-loaded all but the crucial task of locating and engaging the target. By Day 10 I would have been happy to take back more of the tasks such as threat avoidance, navigation and tactical flying to absorb the spare capacity. Heaven forbid a pilot should be bored or feel he lacks control in the heat of the battle - it would do his mental state no good at all! To be serious though, the level of support should depend on his spare capacity and that capacity is often dependent on his experience level. How this interaction is achieved is the difficult exam question but should result in a form of "adaptive automated decision support".

Are there any capabilities that electronic crewmember will be unable to achieve? I

believe the answer to be yes and this returns to my previous reference to flexibility. As far as I'm aware computers cannot replicate the ingenuity of the human mind and this is where the human flexibility wins over. The human can deal with situations which are totally new or unplanned, quickly evaluate the scenario and chart a course through unfamiliar territory - he may call on previous experience but he may also rely on innovation, intuition, imagination and visualisation. The electronic crewmember will, at the moment, lack these qualities and thus flexibility. A question that I have been asked is "can you train for or learn flexibility"? Simply the answer is no. I spent 3 years instructing at our fast jet training school and you could very quickly ascertain if a student had the make-up to succeed. The flexible student quickly assimilated the requirements and could cope with most everything you threw at him. The rigid student had to see something first before he could successfully negotiate the problem. You cannot teach that flexibility (or at least I couldn't).

Another capability which the electronic crewmember lacks is the ability to take calculated risks. In air-to-air combat 2 opponents may be equally capable and it is often the one who makes the first mistake who loses. This may add fuel to the argument that the machine should fly the combat as it will not make the mistake. However, it is often the pilot who takes the risk which wins the engagement. A World War 2 Battle of Britain commander is reputed to have said "don't send me good squadron commanders, send me lucky ones". I believe that you often make your own luck and there are many highly decorated military men who turned the tide of a battle or an engagement by taking a risk. The machine will not take that risk!

In addition, I also believe that, given certain conditions, the human can fly an aircraft lower than the automatics can. The lowest setting that the Tornado Terrain Following Radar can be set for automatic operation is

200 feet. A reconnaissance Tornado was tasked during the Gulf War to go and find the Republican Guard in the Wadi al Batin. The weather and the aircraft sensor capability dictated that the only way to achieve the mission was at low level. As it was perceived to be a high threat area the pilot elected to fly the mission manually using the radar information at 100 feet - the mission was a success. The issue of flight safety criticality will always limit the clearance an aircraft can achieve when flying close to the ground. We in the Jaguar Force trained at 30 feet over the desert - thankfully we never needed it! Could a machine have achieved that even with intelligent vision!

So to conclude. Provided that we approach the problem in a reasoned manner the human electronic crew is the right stuff. It must, however, use the best assets of each element, allowing for the situation that the pilot finds himself in. The requirement is not easy to achieve but we should strive to achieve it. So the real question is what mix is the right stuff - the theme of the workshop.

I hope I have given you something to think about - if not please humour me and buy me a drink later. I wish you all an enjoyable and fruitful workshop.

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# HCI Design Principles for Effective Cockpit Information Management

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## 1. SUMMARY

In order for the human-electronic interface to function effectively, the electronic crewmember, as well as all electronic interfaces must be designed in accordance with human computer interface (HCI) principles and guidelines. The US Department of Defense (DOD) has been working to develop Human Computer Interface (HCI) guides, handbooks, and standardization documents as part of their interoperability and military standards reform initiatives. Few of these documents, however, address the unique HCI requirements of the military aviation operational environment. A need exists for a set of guidelines that can address these unique HCI requirements and serve as a resource during the cockpit HCI design process. The Tri-Service Aviation Human Computer Interface (AHCI) Style Guide recently developed for the US Joint Cockpit Office will fill this need. This paper summarizes the AHCI Style Guide development process and highlights the design guidelines that are most relevant to the design of the electronic crewmember interface.

## 2. INTRODUCTION

The need for cockpit HCI design guidance stems from the rapid development of software and hardware capabilities within the avionics industry, including advances in computers, sensors, data processing, digital data communications, and sophisticated electronic display formatting techniques. The application of these capabilities within the cockpit has led to (1) a profusion of information being provided to the crew members and (2) the increased use of automated systems within the cockpit. A significant result of these trends is an expansion in the crew member's role from an active

controller who directly interacts with individual subsystems, to a supervisory controller who monitors and manages multiple automated subsystems and information sources.

Electronic interfaces now play a central role in the modern cockpit interface, providing the crew with access to flight, weapon, navigation, communications, defensive systems, offensive systems, and other system functions and information. It is critical that these interfaces are designed for both flexibility and efficiency to support a wide variety of crew functions, and to allow the crews to effectively use them in demanding, time-critical conditions. A flexible and efficient interface design would also enable the crewmember to seamlessly transition from one task to another, as required by different mission phases, or in response to a highly dynamic combat environment. In short, the cockpit HCI should be a natural, intuitive interface that supplements and complements the crewmember's own capabilities, procedures and techniques. A source of design guidance and lessons learned to aid designers in achieving these goals, and to aid in standardization for electronic interfaces across systems is needed. The Tri-Service Aviation Human Computer Interface (AHCI) Style Guide is being developed to fill this need.

The AHCI style guide will provide guidance for HCI requirements specific to the military aviation domain. In so doing, the AHCI style guide will extend existing DOD HCI style guides and handbooks. The guidance provided will also help designers comply with DOD interoperability, intraoperability and open systems architecture objectives and standards reform initiatives.

### 3. APPROACH

#### 3.1 Crew-Centered Design Philosophy

The AHCI style guide was developed with an emphasis on a "crew-centered design" philosophy. The crew-centered design philosophy encompasses the view that effective human-computer interfaces are developed through a basic understanding of the functional and information requirements of the operational domain as they relate to the crewmember's capabilities and limitations. This understanding is critical in cockpit interface design because it enables the designer to develop an interface that directly supports the crew in task accomplishment, maintaining situation awareness and preserving aircrew safety.

Following this philosophy, an integrated systems design approach was taken in the development of the guidelines. The integrated systems approach is based on the notion that an AHCI typically consists of a suite of interrelated display hardware, programmable display formats, and control devices that are linked together through dialogs that provide the method by which the crew accomplishes "transactions" with the system. The approach taken for the AHCI style guide emphasizes the interaction between AHCI system components, including the crewmember as an integral component, and the need for an integrated AHCI system to support the diversity and multitude of tasks that the crew must accomplish in the aviation operational environment.

#### 3.2 Operational Considerations

Prior to development of the AHCI style guide, the military aviation operational environment was analyzed to more clearly define the context in which the AHCI design is to be accomplished. This analysis identified several characteristics that are common, to varying degrees, across a broad range of military platforms and missions, and that can have a significant influence on aircrew performance and AHCI design. These include:

- *Information Intensity.* Advances in computer and sensor technology, data processing, and digital data communications have resulted in an enormous amount of information available to the crew in modern military cockpits. The multitude of information currently available, compounded with recent trends in reducing cockpit crew size has created the very real potential for information overload on the remaining crewmembers.
- *Multi-Tasking.* Crewmembers on all aircraft platforms are frequently required to perform multiple tasks simultaneously and to attend to information presented from multiple sources.
- *Time Constrained.* Many missions must be performed and key decisions must be made within strict time constraints.
- *Severe Consequence for Error.* In many missions, especially combat missions, there are mission critical functions that may impose severe consequences for crewmember error.
- *Dynamic Environment.* Many mission can be characterized by a dynamic environment that requires the crewmember to be responsive to real-time changes in tasking and the mission environment.
- *High Workload.* The military aviation environment can often be characterized by high task workload and psychological stress. This is more evident in combat missions, during critical phases of flight, and may become more prevalent with ongoing efforts to reduce crew size.
- *Physical Constraints.* The cockpit environment imposes various physical constraints on the crewmembers that may impair their ability to adequately observe all system displays and reach all controls. The use of night vision goggles, laser eye protection, and nuclear, biological and chemical (NBC) gear may contribute to these physical constraints. The ambient noise and lighting conditions found in some cockpits may also affect the performance of certain tasks.

These characteristics were taken into consideration in the development of the AHCI design goals that form the foundation of the design guidelines presented in the AHCI style guide.

### 4. DESIGN GOALS

The AHCI design goals provide a link between the aviation operational environment and the guidance provided in the AHCI style guide. The guidelines were developed with these overall goals in mind. Taken as a whole, the design goals provide a framework for interface design through the application of the AHCI guidelines. The design goals include the following:

- *Maximize Situation Awareness (SA).* The AHCI should be designed to facilitate crewmember awareness of both external and internal events as they relate to the cockpit tasks. Evidence is accumulating that the loss of SA is a limiting factor on mission effectiveness and plays a significant role in aircraft accidents and incidents. The ability to anticipate events and to plan reactively can ultimately determine the success of a mission. One of the first things that can be done to help pilots achieve SA in a demanding environment is to improve the pilot vehicle interface so that the required

information can be gleaned with a minimum amount of workload. (Endsley, 1)

- *Minimize Workload.* The interface should be designed so that the crewmember can efficiently accomplish all functions required to achieve the mission objectives without exceeding his/her cognitive, perceptual or physical capabilities. Unnecessary workload may be required to find information in a multitude of screens available, acquire information from a given display format while filtering out unneeded or competing information, and to integrate or interpolate data in the form needed for decision making. (1)

- *Provide Efficient Access to Critical Information.* One of the best ways to improve the crewmember's SA and reduce workload in a demanding environment is to design the interface to provide access to critical information with minimal effort required. The AHCI should provide task-relevant information, rather than raw data, to minimize the need for the crewmember to mentally integrate information from multiple sources. It should also allow the crewmember to quickly locate and extract critical information in response to changes in the mission environment.

- *Maximize System and Mode Awareness.* The interface should be designed to facilitate crewmember cognizance of the aircraft systems and automation mode state. As aircraft subsystems become more automated, modes have been increasingly used as a general method of human-automation interaction. One characteristic of modes is that the same pilot action may result in different system behavior depending on system mode. Thus, mode confusion can result when the pilot misinterprets the current mode state or the transitioning from one mode to another. Pilot error resulting from mode confusion is considered to be a significant contributor to accidents involving highly automated aircraft. (Degani, 2)

- *Minimize "Head-Down" Time.* To the extent possible, the AHCI should be designed for "head-up" operation, and to minimize "head-down" time. Such a design will enable the pilot to maintain awareness of critical information in the external environment. Overly complex interfaces can draw the crewmember's attention "head-down" and can result in fixation on a single system or display, distracting the crewmember from attending to mission-critical information.

- *Conform to "Hands-On" Design Philosophy.* A "hands-on" design philosophy helps to improve multi-tasking in a high workload environment. Locating frequently needed or critical switches on the controls allows the crewmember to easily access the controls while performing the primary task of flying the aircraft.

Hands-on control allows for a more immediate and effective operation during the most critical phases of flight. The design also provides a more direct interface that promotes smooth transitioning among various control tasks with minimal physical and mental effort.

- *Minimize and Effectively Manage Errors.* The interface should be designed to reduce the potential for error and facilitate the recovery from error should one occur. Within the cockpit, there are many mission critical functions that impose severe consequences for error. Even when the error is not critical, the crewmember must determine the cause of the problem and how to recover from the error. This may require additional head-down time, increase crewmember workload, and detract from the accomplishment of other mission tasks. To effectively manage errors, the interface should be designed to 1) minimize the chance of errors, 2) minimize the consequence of errors, 3) promote the detection of errors when they occur, and 4) facilitate the correction of errors once they are detected. (Norman, 3)

## 5. AHCI DESIGN PRINCIPLES AND GUIDELINES

### 5.1 Guideline Development Process

The design goals served as the framework from which the guidelines were developed. The AHCI guidelines were derived from relevant HCI specifications and standards from the military services and various commercial establishments. Principle among these documents was the DOD Technical Architecture Framework for Information Management (TAFIM, 4). Where existing guidelines were not available, they were generated based on published HCI and cockpit research results. These guidelines were then tailored to the specific aviation domain taking into consideration the typical AHCI components, their role in the overall cockpit interface, and the aviation operational environment.

### 5.2 Guideline Categories

Understanding that the AHCI is made up of display hardware, programmable display formats, and control devices, the style guide development team concluded that it was necessary to provide guidelines on designing each component of the AHCI. The style guide provides guidelines for typical AHCI components and also provides guidelines on integrating these components with each other and into the cockpit as a whole. By providing guidance on each component as well as the integration of these components, the AHCI style guide presents HCI and human factors design principles as

they apply specifically to the unique problem of aviation cockpit interface design. After compiling the guidelines relevant to AHCI design, it was evident that the guidelines fell into four major categories; one category that encompasses high-level, system integration issues, and three categories, each dealing with a specific component of the AHCI. The AHCI guidelines are presented in the following categories:

1) *Cockpit Information Management* guidelines provide system-level design guidance for managing cockpit information for integrated AHCI system design. These guidelines were developed with the understanding that the integrated cockpit design, as a whole, is greater than the sum of its individual component designs. Thus, cockpit information management functions are addressed in the context of designing an integrated AHCI that will facilitate the crewmember in task and information management, and in acquiring and maintaining situational awareness. Guidelines in this category address several topic areas including: consistent and predictable interface; system compatibility for task management; information presentation and integration; display management; designing for crew coordination; interacting with automated systems; mode management; and effective use of decision aids.

2) *Dialog* guidelines provide guidance for the design of dialogs that allow the crewmember to communicate and interact with the aviation information systems. A dialog is defined as a structured series of HCI transactions (crewmember actions paired with system responses). Typical dialog types include menus, graphic interaction, alphanumeric data entry, and direct system command.

3) *Information Presentation and Formatting* guidelines provide guidance for the display of information on electronic media. Specific issues addressed within this category include display coding, textual displays, auditory formats, and graphical and integrated formats.

4) *Displays and Controls* guidelines provide guidance for a variety of control and display devices typically implemented in the AHCI including hands-on controls, cursor devices, pushbuttons, keyboards, multi-function displays, helmet-mounted displays, and head-up displays.

### 5.3 Example Guidelines

The context of this paper does not allow for the presentation and discussion of each guideline contained in the AHCI style guide. However, the following example guidelines are presented to give the reader a sense of the intent of the AHCI Style Guide and the

diversity of the guidelines that are applicable to cockpit human-computer interface design.

#### 5.3.1 Information Management Guidelines

*Consistency Across Functions* - Where possible, the cockpit interfaces for different functions should be consistent and predictable in terms of system and automation logic, format schemes, organizational schemes, coding schemes, usage of symbols and abbreviations, control responses, interface dialog mechanization and feedback.

*Display Formatting Consistency* - Display formats should have a consistent structure and layout for similar functions. Identical or similar types of information or display elements should be displayed in a consistent manner, regardless of the source of origin. Information encoding schemes used throughout the interface should be consistently applied to identical or similar types of information.

*System Compatibility with Task Requirements* - Displays, controls and dialogs should be functionally compatible with the crewmember and task requirements, to promote an efficient means of accessing and acting upon task-relevant and critical information. As a minimum, displays, controls and associated dialogs should be: 1) optimized for task requirements, 2) consistent with crewmember conventions and expectations, 3) facilitate the crewmember's ability to quickly switch attention across multiple information sources and 4) minimize the potential for error especially when under time-stresses and high workload conditions.

*Direct Access of Information* - Information should be presented to the crewmember in such a way as to facilitate the crewmember's ability to detect and interpret information, while placing minimum demands on the crewmember's perceptual, memory, and cognitive capabilities. This is applicable to the selection of display modality (auditory, visual, tactile), the specific information content presented, the format of information presentation within the modality, and the level of precision at which the information is presented.

*Direct Access of Primary Flight and Critical Information* - As a minimum, the system should continuously inform the pilot of: 1) primary flight information, 2) essential information for the accomplishment of the mission tasks and 3) currently selected system, subsystem or display/control modes. Other information requirements should be based upon mission, task and information analyses.

**Prominent Display of Essential Information** - Essential information required for task accomplishment should be readily available and predominately displayed at the forefront of the crewmember's awareness. This includes information that is commonly used, frequently cross-checked, or time-critical. Conversely, the amount of non-essential information should be minimized.

**Task-Based Organizational Structure** - Information, controls, and options should be segregated into functional groups and organized on the basis of some logical principle. Major tasks and associated display pages should provide the predominant structure for the interface.

**Tailoring Display Options** - The crewmember should be given some capability to control the amount, format and complexity of displayed information to meet task requirements. This includes designating the display of interest, defining cockpit display configurations, selecting formats, and defining default configurations during system set-up.

#### 5.3.1.1 Automation Guidelines

**Resource Allocation** - An automated function should be easier to operate than the manual function it replaces. Repetitive and predictable tasks should be allocated to the computer. Tasks that are performed in an unpredictable environment, require flexibility and adaptability, or goal-setting and switching should be allocated to the human.

**Automated Output** - As a minimum, automated systems should: 1) provide sufficient information to keep the crewmember informed of its operating mode, intent, function and output, 2) inform the crewmember of automation failure, 3) inform the crewmember if potentially unsafe modes are manually selected, 4) not interfere with crew manual task performance and 5) be designed to allow for manual override.

**Disruption of Task Performance** - Ensure that automation does not disrupt the performance of the task. Design control automation to be of the most help during times of highest workload and less help during times of lowest workload.

**Automation Delimited in Authority** - Control automation should not be able to endanger an aircraft or make a difficult situation worse. It should not be able to cause an overspeed, a stall, or contact with the ground without explicit instructions from the pilot.

**Crewmember Involvement** - Keep the crewmember involved in the automated operation by requiring of them meaningful and relevant tasks, regardless of the level of management being utilized by them. (Note:

High levels of strategic management have the potential to decrease pilot involvement beyond desirable limits. Keeping pilots involved may require less automation rather than more, but involvement is critical to their ability to remain in command of an operation and reenter the loop in case of a failure). (Billings, 5)

**Control Automation Flexibility** - Control automation should provide the human operator with an appropriate range of control and management options.

#### 5.3.1.2 Mode Management Guidelines

**Mode Awareness** - The AHCI design should facilitate crewmember's awareness of current mode state and the potential interactions among modes, especially during critical points or phases in the flight.

**Transitioning Between Modes** - The crewmember should have the capability to easily switch between modes. Features and functions that are common between display modes should be as consistent as possible.

**Mode Indicator** - Design display/control modes to be visually distinctive or provide some visual indication to make the current mode easily identifiable.

#### 5.3.1.3 Decision Aids Guidelines

**Use of Decision Aids** - The designer should consider using decision aids for managing system complexity, for assisting the crewmember to cope with information overload, and for focusing the crewmember's attention. Decision aids may also be useful for overcoming the following human limitations: a) dealing with uncertainty, b) overcoming emotional components of decision making, c) memory and information-retention problems, and d) systematic and cognitive biases.

**Meaningful Patterns** - A decision aid should automatically notify the crewmember of meaningful patterns or events. A decision aid should predict future data based on historical data and alert the crewmember when it predicts a future problem.

**Data for Making Judgments** - Decision aids should provide data on which to base judgments rather than commands that the crewmember must execute.

**Feasible Alternatives** - If available, a decision aid should provide several feasible alternatives from which the crewmember can choose.

**Awareness of Input Logic** - Provide the crewmember with an understanding of the decision rules and logic that the decision aid algorithm is utilizing.

### 5.3.2 Dialog Guidelines

**User-Paced Sequence Control** - Allow the crewmembers to pace control entries, rather than requiring the crewmembers to keep pace with computer processing or external events. This will allow control entries to be made in accordance with the crewmember's current needs and available time.

**Feedback for Crewmember Actions** - Provide the crewmember with feedback for menu selections, data entries, graphical selections, control actions, direct system commands, or other input to indicate that the action has been accepted or not accepted. For every action by the crewmember there should be some apparent reaction from the system.

**Error Handling and Feedback** - The HCI should be designed to provide simple error-handling, both by system error-checking and ease in correcting an identified error. Ensure that the system provides a clear indication and explanation of error conditions.

**Menu Structure Based on Task Analysis** - Design cockpit menu structure and organization based on a mission-level human factors engineering task analysis. Consider organizing menus around subsystems or operational modes, with each subsystem or mode functionality accessible from a top-level menu option.

- **Menu Tree Structure Appropriate to Cockpit Application** - Limit the levels in cockpit menu applications (3 levels is typically recommended) so that the menu tree structure is broad and shallow rather than narrow and deep. Crewmembers can easily become lost in deep levels especially during critical tasks within the aviation operational environment.
- **Menu Type Distinction** - When different menu types are used within the same cockpit application, there should be a unique indication that denotes the type of menu and the actions required of the crewmember.

**Graphical Element Selection** - Provide the crewmember with a means for designating and selecting displayed graphic elements. Ensure that it is clear to the crewmember which graphical elements are selectable and how the elements are to be selected. When the element is selected, ensure that it moves to the foreground to guarantee that it is not obscured.

- **Element Selection Area** - Ensure the selection area for graphical elements is of appropriate size to enable the crewmember to easily select the elements under all operational conditions. The selection area must be large enough so that the

crewmember can accurately position the cursor under operational flight conditions such as vibration and g's.

- **Selection Sensitivity to Vibration** - When objects are selected using a pointing device, ensure the selection method is not sensitive to the inherent vibration of the aircraft.
- **Limit Need for Multiple Entry Devices** - Design the graphical interaction tasks so that control actions as well as element selection is accomplished by the same input device to limit the need to shift from one entry device to another.
- **Confirming Selection** - For most graphic applications, pointing and selection should be a dual action, first positioning a cursor at a desired position, and then confirming that position to the computer.

### 5.3.3 Information Presentation and Formatting Guidelines

**Layout/Organization of Information** - The layout of information within a page should follow some logical, organizing principle that crewmembers can recognize and apply. Data should be grouped on the basis of this principle, considering the trade-offs derived from task analysis. Groups of data should be distinctively displayed using blank space, surrounding lines or different intensity levels as appropriate. Ensure that the location of recurring functional groups and individual items is consistent across MFD pages and displays.

- **Integrated Format** - When the crewmember is required to assess the relation among different data elements, the data should be provided in an integrated format rather than partitioning them into separate windows or display pages.
- **Display of Trend Information** - Format and display information to enable the crewmember to easily acquire historical trend information for those tasks that require some estimate of this information for task accomplishment.

**Content of Display Information** - The content of displayed information should be that which is best suited for the crewmember at any given point of time.

- **Information Quantity** - The quantity of information displayed to a crewmember should be limited to that which is necessary for the performance of specific tasks, maintaining situation awareness, or the making of decisions.
- **Information Precision** - The precision of the information displayed should be at the level

necessary for the accomplishment of crewmember actions or decisions.

**Usable Form Consistent with Crew Conventions** - Display data in the most directly usable form so that the crewmember is not required to transpose, compute, interpolate, or mentally translate data into usable units, or number bases. Display information only as accurately as the crewmember's decision and control actions require. Also display data in a format that is consistent with crewmember conventions and that uses familiar wording or task-oriented jargon.

**Display Clutter** - Displays should be as uncluttered as possible. Information should be presented simply and in a well-organized manner and the display should appear clutter free.

- **Display Density** - Display density should not exceed 50%, and preferably should be less than 25%. Density should be minimized for displays of critical information. The unused area of a display page should be distributed to separate logical groups and categories of data.
- **Prioritizing Critical and Non-Critical Information** - Minimize the information density on a display by prioritizing and limiting information to be displayed. Prioritize the information so that the most important or critical information is displayed at all times and less important or critical information can be displayed upon crewmember request.
- **Display of Unnecessary/Old Data** - To help alleviate display clutter, unnecessary borders should not be used on the display. Scales should not be cluttered with more marks than necessary for precision. Old data points should be removed after some fixed period of time, and interim information should be removed from the display once it is no longer needed.
- **Declutter Scheme** - The designer should develop a hierarchy of information needs and incorporate this hierarchy into a compatible declutter capability.
- **Crewmember Capability to Declutter** - Whenever possible, provide the crewmember with a means for reducing clutter while preserving essential information.

## 6. CONCLUSION

The above guidelines give the reader a brief, high-level representation of the type of design guidance provided in the AHCI Style Guide. Taken as a whole, the guidelines contained in the style guide will promote development of an integrated cockpit interface that effectively supports the crewmember's role as system, task and information manager within modern military aircraft. A draft version of the style guide is currently being reviewed by tri-service representatives, as well as representatives from academia and industry. It is hoped that once approved, this document will become widely accepted as a useful tool in the development of modern cockpit interfaces.

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## Abstract

This paper describes the range and scope of laboratory prototype Knowledge Based Decision Support systems for Maritime Air applications conducted by the KBS Group at DERA Farnborough UK. The rationale behind the choice and development of the requisite tools and software are described. The applications include Decision Support for Anti Submarine Warfare (ASW), and Anti Surface Warfare (ASuW) together with an ASW/ASuW Technology Demonstrator.

## 1.0 Introduction

### 1.1 KBS Group Background

The Knowledge Based Systems Group within Systems Integration Department at the Defence Evaluation and Research Agency (DERA) in Farnborough have been engaged for more than a decade in research and applications of knowledge based decision support. (Ref 1) The initial impetus was the general search for a means of managing aircrew workload. Mission systems were being specified for airborne use where manufacturers claims for improvement in mission performance were high but without corresponding assessment of the role of the aircrew required to attain such performance levels. From earlier work by the core team members on less sophisticated airborne systems the indications were that the newer proposed mission systems would generate a wake of different, additional attentional demands. The emergent technology of expert systems was then considered as a potentially useful avenue to explore.

### 1.2 Shells and Limitations

The then new LISP based Expert Systems shells such as Inference Art and Intelicorps KEE, together with lesser known proprietary products were acquired and experience gained in diagnostic level problems such as replicating aircraft warning panels. Experience in

devising and using structured interview techniques in problem identification and assessing performance in Human Factors studies where more reliable measures were not available enabled the team to build skeletal laboratory demonstrators when coupled with the commercially available shells. Whilst the early experiences with the shells indicated the potential of the approach in functionally representing the required salient features in narrowly focused airborne domains the software speed limitations rapidly became apparent.

### 1.3 Application Expansion

It was realised that the fundamental design of LISP posed an impediment to the real time demands of airborne applications. To extend the laboratory demonstrators to capability which would interest military customers would require faster software and prototype build methods far beyond those commercially available. The group proposed that more systematic methods of knowledge acquisition, a more appropriate form of validation methodology were needed for Knowledge Based Systems (KBS) development together with a real time capability more in line with airborne requirements. This would require considerable research investment, but coincidentally, the United States Government General Accounting Office (GOA) report published in 1981 drew attention to financial implications of continually assuming that the increasing significant elements that system designers were unable to specify in complex military systems could be compensated for by the ingenuity of human operators.

### 1.4 Realisation

Following the publication of the GAO report, a NATO Working Group was set up and reported in 1984 that KBS should be examined as one possible means of addressing such problems. (Ref 2) One of the authors was a member of the NATO Working Group and used the rationale for the need for research funding that if expertise was needed to generate

complex systems, if that expertise could be incorporated in computer code within the mission systems as advice then overall mission performance ought to improve. Such arguments were successful and paved the way for the large scale UK-MOD funded research programme covering KA methods (PC PACK) (Ref 3) real time software (MUSE and D-MUSE) (Ref 4) and a validation methodology (VORTEX) (Ref 5) which currently are being applied to demonstrators for knowledge based decision support for Maritime Air applications.

## 2.0 The First Maritime Air Application - Anti Submarine Warfare (ASW)

Previous background by the author in human factors assessments of Maritime Air sensor and mission systems led to an awareness that the task was characterised by a developing situation where fine judgements were examined rather than the more deterministic reactions encountered in strike mission management. When an application was needed to evaluate the capability of the validation methodology research which recommended a spiral development life cycle for rapid prototypes for KBS workstation demonstrators then the developing nature of the maritime mission was seen as an appropriate application to demonstrate the concept of KBS. (Ref 6) The skeletal Anti- Submarine Warfare (ASW) scenario used proved doubly effective in demonstrating the tools designed for validating the knowledge base and when combined with the measures of effectiveness defined by the maritime customer illustrated that the tactical advice offered exceeded the customer expectation of the laboratory demonstrator. (Ref 7) The Validation of Real Time Expert Systems (VORTEX) application had been written in LISP due to the groups experience with LISP based shells. At that stage it would have been difficult to make the case for funding a separate line of software development due to the large scale US-DARPA investment in LISP during the initial phase of the Pilots Associate Programme. (Ref 8) However, the Group's experience in sponsoring the development of the real time software development toolkit (MUSE) and its successful application in a laboratory demonstration of a multi engine helicopter warning panel and its performance on tapes provided by NASA Ames on telemetered systems status data from the X29 research aircraft provided sufficient evidence in its potential to secure additional funding. The next expanded version of the ASW application which focused on producing a decision support system for controlling more than one platform used MUSE rather than LISP.

## 3.0 The Second Maritime Air Application - Anti Surface Warfare (ASuW)

At the same time that the group was developing the LISP funded ASW demonstrator for the validation methodology evaluation, parallel effort was also being expended in applying MUSE to a skeletal mission manager workstation demonstrator using a fixed wing strike scenario. (Ref 9) Compared with earlier success of using MUSE with diagnostic applications with multi engine helicopter warning panel and the NASA X29 data the different data types and varying input frequencies began to reveal limitation in the real time performance of the MUSE software. Additional research funding was then received to develop a multi agent real time capability (D-MUSE) to maintain the software performance against the more demanding scenarios envisaged. Maritime air experience during the Gulf War had revealed the difficulties in tracking high speed fast patrol boats which would also camouflage their presence by mooring alongside oil rigs or inserting themselves in slow moving fishing fleets. This application was considered ideal to assess the real time capabilities of the multi agent software and so a knowledge based Anti Surface Warfare (ASuW) decision support system workstation demonstrator was built. (Ref 10)

## 4.0 Aircrew Roles in ASW/ASuW Aircraft

Maritime aircraft are required to operate world-wide, often at short notice and in a variety of roles. To fulfil such demanding requirements the aircraft carry very sophisticated sensors and complex systems which are configured and managed by the aircrew to most effectively meet the needs of the varied missions. Such variation in operating environments and improved capabilities of future mission systems led to the increasingly demanding role for aircrew. This role is characterised by:

- 1 A need to adequately consider the most appropriate mode in which to operate a sensor due to the increased number of modes.
- 2 The need to handle a vastly increased volume of data provided by improvements in sensor performance. This is generated by the increased number of targets likely to be seen over longer ranges. The lower signal to noise ratios at which detection is possible also increases the number of false contacts.

3 Greater uncertainties being generated regarding track identity, position, course and speed due to the difficulties in classifying and localising targets at longer ranges.

4 Data from different sensors needs therefore to be combined in order to improve the confidence in track identity, position, course and speed. This requirement to use sensors co-operatively, dynamically reviewing the combination, create a significant challenge to aircrew.

5 Reduction in contact time for sensors results from continuing improvement in threat performance so that the window of opportunity for aircrew to detect, recognise and react to new contacts is diminishing.

The increasingly demanding role imposed on the aircrew and the associated time criticality associated with the necessary decision making based on assimilation, integration and interpretation of data from a multi-sensor mission system therefore lends itself to a knowledge based decision support solution.

For the Anti Submarine Role (ASW), the aircrew tasks (UK Observer, US Tacco) which could be addressed by applying KBS technology would be:

- 1 Deployment of Active Dipping Sonar and sonobuoy screening barriers
- 2 Active and passive location
- 3 Attack and re-attack
- 4 Lost contact procedures
- 5 Management of assets

Similarly in the Anti Surface Warfare role (ASuW) the aircrew tasks would be:

- 1 Classification of surface sensor data
- 2 Generation of surface picture based on classification
- 3 Path predicted for associated tracks
- 4 Plan area search routes
- 5 Assign contacts
- 6 Route production for confirmation of identity and hostility level of tracks

## 5.0 The ASW/ASuW Technology Demonstrator Programme (TDP)

### 5.1 Background and Rationale

Other departments within DERA, particularly those associated with airborne and submarine surface sonars and anti air warfare in surface ships had also been examining and applying expert system

technology. The Maritime Air Customer decided that a Technology Demonstrator Programme or US/ATD be mounted as a risk reduction exercise before considering the exploitation of Knowledge Based Decision Support technology in a mission system for the next generation of ASW/ASuW airborne platforms. To test the need for such decision support and to establish the breadth of functionality required structured interviews were conducted with authoritative sources of future operational requirements for maritime airborne platforms, DERA research sites and contractors engaged in developing workstation demonstrators. A functionality matrix was used incorporating a weighting schedule agreed by interview participants to establish need for and the functionality demanded of a decision support system to manage workload, maximise the use of mission systems and sensor resources to achieve consistency of mission performance.

### 5.2 Organisation and Components

Having agreed the need and functionality required for ASW/ASuW decision support the many workstation demonstrators developed under the sponsorship of DERA but targeted at specific areas of functionality were assessed for their relevance to the declared aim of satisfying the Maritime Air Customer requirement. A rainbow consortium of contractors had been formed in order to manage the intellectual property rights aspects and exploit the specialist experience of teams engaged in the wide range of small scale laboratory demonstrators. Representative threat scenarios were provided by the maritime Air Customer. The Rainbow Consortium included contractors with experience of building workstation demonstrators in the target domain, simulation environments to evaluate such demonstrators, data fusion systems and software to implement such schemes. These building blocks under consideration for the TDP included 7 separate workstation demonstrators, 3 simulation facilities, 2 computer simulation environments, 2 real time software toolkits and a data fusion system. Evaluation of building blocks was conducted using a selection strategy based on weighted requirements matrix including tasks defined in the approved scenarios together with functionality requirements. (Ref 11) This assessment having been achieved allowed the optimum architecture to be defined together with the associated components. Examination of maturity levels, flexibility and implementation considerations in association with a cost/benefit analysis led to the selection of the architecture and necessary components to achieve the core decision support

system to implement the desired level of complexity to influence the Maritime Air Customer of the potential of the technology. This rigorous evaluation and trade off study resulted in the selection of an architecture which included:

- 1 A computer simulation environment, hosted on workstation which incorporated ASW and ASuW modelling capability.
- 2 A data fusion/association capability based on AAW Frigate TDP and ASW mission system.
- 3 The ASW and ASuW decision support laboratory workstation demonstrators.
- 4 The real time, multi agent software development toolkit D-MUSE due to its level of maturity; richer selection of programming strategies; represented the core of the key building blocks and could be interfaced to the simulation environment.

### 5.3 Complexity

Further additional tasks are under discussion for inclusion by the contractors and the Maritime Air Customer in order to increase the capability of the ASW/ASuW Knowledge Based Decision Support Technical Demonstrator Programme. Man-in-the-loop evaluations are planned in order to demonstrate military worth of knowledge based DSS for the Maritime Air Customer. It can be seen that the nature and complexity of the tasks are very different from those usually encountered in the literature. A recent NATO KBS Working Group reported that KBS technology was sufficiently mature for applications in aeronautics and space due to their potential having been demonstrated in France, Germany and the USA in diagnostic and planning tasks in fielded systems. (Ref 12) More multi-function systems incorporating complex architectures were reported as being between the laboratory and fielded systems. The Maritime Air TDP described in this paper represents such an interim system.

## 6.0 Situation Assessment

### 6.1 Significance

A crucial element of the TDP and one which embodied many of the questions associated with the search for progress mentioned in the workshop calling notice is that of Situation Assessment. Situation Assessment (SA) is a process where an assessment of the compiled tactical picture is made with the aim of extracting information that can help aid the decision making process. In the Maritime environment this process can be performed by naval

personnel at all levels: an operator examining a radar display, a ship's Air Warfare Officer assimilating information about aircraft that are transiting within sensor range, an Airborne Early Warning observer ascertaining the type and role of an approaching aircraft. The importance of the SA process has already been recognised by the most of the designers of knowledge-based applications and this is shown in the number of decision support systems that utilise elements of SA.

### 6.2 Difficulties

One of the greatest problems experienced in designing a system that performs SA is that it is often difficult to obtain an objective description of the tactical picture. When a group of domain experts are presented with a tactical picture that has little historical data associated with it they will very often give different, but not entirely dissimilar, opinions of what they are seeing. The best that anybody who performs knowledge acquisition with a group of experts can hope for in the absence of a structured methodology is a general consensus of opinion. This is just one reason why it is often difficult to implement large-scale knowledge-based SA systems because if its output is based upon the consensus of one group of experts then more often than not there will exist another group of domain experts who will disagree with it. A solution to this problem is to use official documentation about the domain and couple it with the knowledge that has been elicited from the domain experts. For the purposes of the TDP this has been official ASW/ASuW tactic manuals known as TACMAN. The accuracy of the output of a system carrying out SA can be severely hampered by a number of reasons, such as an incomplete knowledge base caused by inappropriate methods of knowledge acquisition. Even if the knowledge base is complete it may still fail to correctly assess the tactical picture because a target has not been in contact for very long because of the limitations in the detection range of the sensors, or the type of data that the SA system requires is not complete, or consistent, and the system does not possess the reasoning capabilities or the inherent knowledge necessary to overcome this problem.

### 6.3 Solutions

The main reason for the existence of the latter problem is that early attempts at computer based SA had been rule-based implementations that have concentrated on formulating just one opinion about one particular target or a group of targets. It is

inherent that rule-based reasoning systems are fairly inflexible, especially when there is incomplete data, because of their foundations in logic. Despite these problems rule-based systems are still one of the most popular ways of implementing knowledge bases due to the natural way of representing domain knowledge and for their legibility to domain experts. To overcome the problem of dealing with incomplete data recent approaches, as used in the decision support elements of the TDP, have advocated a multi-agent based multiple hypothesis approach when assessing the identity, role and intentions of a target whereby the agents will use domain knowledge to create a hypothesis and communicate it to other agents in the system. With this approach the SA system will perform its functions in a manner that it not too dissimilar to that of the crewman executing the same task. As more information becomes available about a particular target, or group of targets, the system's agents can create, update or eliminate multiple hypotheses about them. This is the same method used to perform battlefield SA in the US Army Rotorcraft Pilot's Associate programme (Ref 13). A multi-agent system may be designed to use a selection criteria to assign the target the same values as the highest scoring hypothesis. Alternatively the system may be designed to repeat the elimination process until such time as when there is sufficient data as to justify the existence of just one hypothesis which is then used as output. The advantage of such systems is that they can offer alternative hypotheses about targets which may allow a decision support systems to calculate more than one solution to a problem (Ref 10)

#### 6.4 Complexity

One of the biggest problems of designing a system that performs SA is how much domain knowledge should such a system possess. Should it be able to produce information about a tactical picture that is suited to one or more tactical decision support aids, or should it be designed to perform an assessment and then tailor its output in a format that will allow existing and future tactical decision support aids to fully exploit it. Essentially this is a question of whether the SA system's knowledge should be task specific or more generically based upon the type of information that naval personnel retain about the operating environment. With the task specific approach, the knowledge that is encapsulated in the decision support system is orientated to deal with all the functions that need to be performed to complete the task successfully. A generically based SA system would be required to encapsulate knowledge not just

about the specific tasks that are required to be performed but also experiential knowledge about the operating environment that would allow it to ensure the information that it was formulating about the tactical picture was complete and consistent with that environment. An example of such experiential knowledge would be to allow the SA system to know what the mission objectives were of the host platform as well knowledge about the tactics used by the known enemy. The system would then be able to reason more adequately and replicate human decision making more closely. However the inadequacy of acquisition methods to construct the completeness required would appear to currently limit the scope of generically based SA systems. As the tasks that the TDP is to perform were clearly defined through an extensive process of knowledge acquisition it was decided that task specific SA would more accurately represent that found in the operating environment and so was included as part of the tactical decision support systems.

#### 7.0 Conclusions

In a recent journal article, Hayes-Roth, drawing on two decades of research experience for DARPA, contended that much has been achieved using AI techniques in an incremental fashion in relatively small scale exercises. (Ref 14) However effort needed to be concentrated over a period of time in specific domains to demonstrate potential before adapting and transferring solutions to new situations. Context adaptable building blocks, re-useable knowledge and composite architectures for multi task systems were recommended as necessary constituents of a future strategy for AI. The authors' of this paper contention would be that in concentrating on Maritime Air ASW (Ref 15), ASuW, (Ref 16), AEW (Ref 17) for almost a decade, and in developing the necessary support software tools and methodologies, together with the re-use aspects as discussed by Prof. Shadbolt, the KBS Group within the DERA organisation in the UK already conform to most aspects of the Hayes-Roth paradigm. New ground is also being broken in the Maritime Air domain as represented at this workshop in the papers by Zancanato and Davies on architectures and designs for Airborne Early Warning, Prof. Shadbolt on Knowledge re-use and updating, and Mc Cloud on validation and certification. A recent US survey indicated that the KBS tool and consultancy market within North America was \$258 Million but reported that the activity in the UK remains conservative in development and deployment of expert systems. Maritime Air is certainly an exception to this

generalisation but awareness is no doubt limited due to exposure being confined to forums such as this workshop.

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# The Electronic Crewmember for Future Commercial Air Transport Operations : Fantasy or Reality ?

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## SUMMARY

Considerable efforts have been spent on the development of intelligent crew support systems for commercial transport aircraft. This paper is intended to reflect briefly on crew assistance systems of the past and to describe the state-of-the-art of electronic crewmembers for commercial transport aircraft. Finally, the application of intelligent crew support in commercial aircraft within the immediate future is being discussed.

## 1. INTRODUCTION

The role of the crew in today's automated flight deck of commercial transport aircraft is being reviewed and discussed each time an incident or accident cause has to be attributed to „human error“.

In the past, the aerospace community tried to overcome the limitations of the human as a real time operator by increasing automation. This approach, however, failed completely. One could observe a change in the type of errors, but the accidents due to human error still account for some 75 % of the overall accidents.

In the early 1980's, it was realised that an automation of more and more pilot tasks can not be the solution to the aircraft safety problem. The focus of attention shifted towards the division of functions between the human crew and the aircraft systems.

In parallel, a new scientific discipline arose , the so-called Artificial Intelligence. And soon the idea of an Electronic Crewmember with human-like knowledge and extensive reasoning capabilities in order to solve problems came up.

The perspective was overwhelming : Having an on-board computer system that complements the human crew, capable of solving complex decision problems in

fractions of a second, not suffering from exhaustion in high-activity flight phases and boredom in low-activity parts of the flight. And, finally, a tool that might detect and prevent any possible pilot error.

This paper is an attempt to reflect on 15 years of research and development work on intelligent assistant systems for the transport aircraft and to outline the future application in operational systems.

## 2. HISTORY OF AUTOMATION

The basic task of a pilot is to stabilise the aircraft and to steer an intended flight path by manual operation of the primary aircraft controls, i.e. elevator, aileron and rudder. Figure 1 depicts this basic control loop, which gives immediate feedback to the pilot with regard to the actions taken.

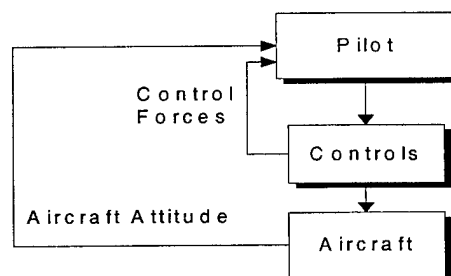


Figure 1 : Basic Aircraft Control Loop

From the early days of aviation, aircraft designers tried to reduce the pilot's workload by automation. It started with simple wing leveller systems that stabilised the aircraft around its longitudinal axis, and led to a first level of crew assistance in the so-called „autopilot“, which provide automatic capture and hold of flight path parameters, like heading or altitude. This automation step, as outlined in figure 2, separated the pilot from direct control of the aircraft and cut him off the control force feedback.

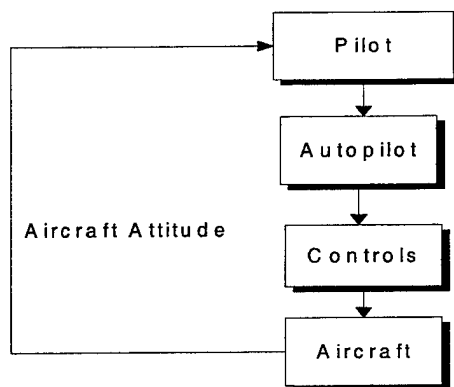


Figure 2 : First Level of Crew Assistance

The next logical step was based on the question : Where does the autopilot input come from ? Who, for example, defines the intercept heading to an assigned track ? This was the origin of „flight guidance systems“ that feed information into the autopilot, separating the pilot from the direct control by two layers (figure 3).

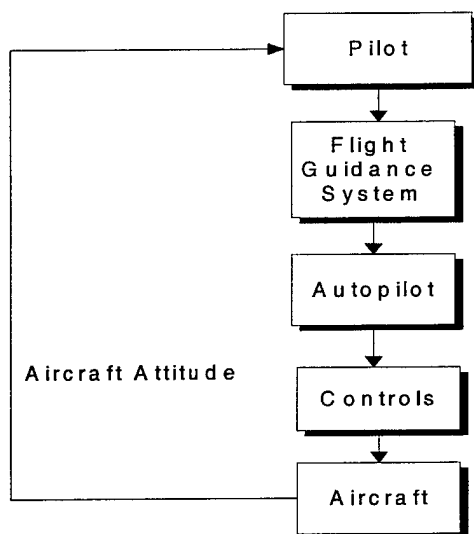


Figure 3 : Second Level of Crew Assistance

The most sophisticated step in automation for crew assistance was the „flight management system“ (FMS). Figure 4 shows the present situation, with the FMS as additional layer between crew and aircraft.

Now the crew can program a complete flight plan into the FMS, which decomposes the information and feeds the proper inputs into the flight guidance system, which in turn controls the autopilot, that finally flies the aircraft.

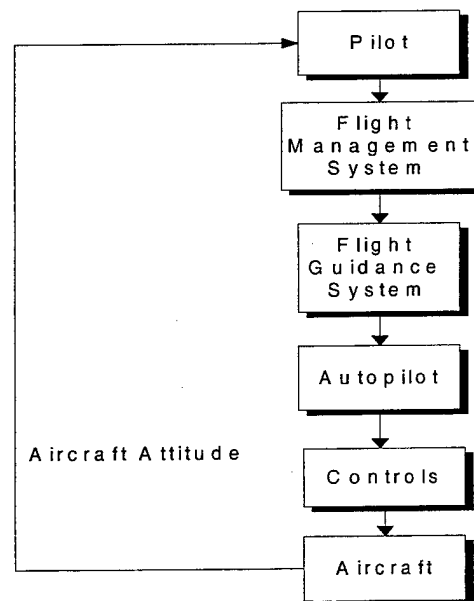


Figure 4 : Third Level of Crew Assistance

Now and then, this procedure ends in a mountain, like the Cali accident proves, where the crew programmed a wrong navaid into their FMS. They never became aware of their mistake.

One logical step ahead - from the perspective of automation - could now be the „electronic crewmember“ that finally eliminates the crew from the flight deck ( figure 5 ).

While this - for obvious reasons - might be a sensible approach for military fighter aircraft, an application in commercial aircraft is unthinkable.

The concept of an electronic crewmember or crew assistant is rather that of an intelligent support system that complements the crew in order to make the best use of their resources and capabilities.

As defined by Onken [ 1 ], an electronic crewmember ( or „Crew Assistant“ ) has the following functional requirements :

1. *Within the presentation of the full picture of the flight situation it must be ensured that the attention of the cockpit crew is guided towards the objectively most urgent task or subtask of that situation.*



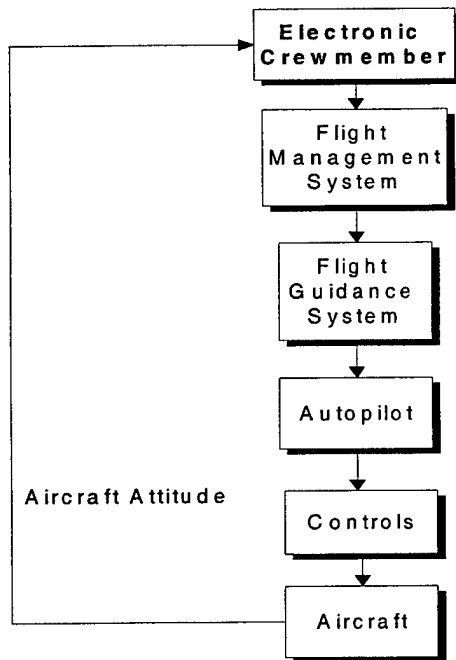


Figure 5 : Crew Elimination

2. *If the first basic requirement is met, and if a situation still comes up with overcharge of the cockpit crew (in planning and plan execution), then this situation has to be transferred, by technical means, into a situation that can be handled by the crew in a normal manner.*

From these requirements one can easily infer that an electronic crewmember must be characterised by :

- a knowledge base representing the knowledge of the flight domain and aircraft operation domain, and
- a model of the crew's behaviour and resources, and
- reasoning capabilities in order to continuously assess the flight situation and crew behaviour, and
- capabilities to put tasks or functions into the context of the current flight and crew situation and to carry them out autonomously.

It is quite obvious, that these features define a system totally different from those automated assistance systems outlined before.

The division of tasks between the human crew and the electronic crewmember should be adaptive according to the situation and should take into account the available crew resources. Figure 6 outlines the basic principle. Figure 6 indicates that an EC has to be seen as a complement to the pilot, not as a substitute. In each step of the situation assessment and decision process chain, the EC may support the crew, if necessary. Possible

hints to important situation elements and alerts with respect to the situation as a whole fulfil the EC requirement #1. EC generated proposals for further actions and the possibility to execute them on pilot's acknowledgement meet the EC requirement #2.

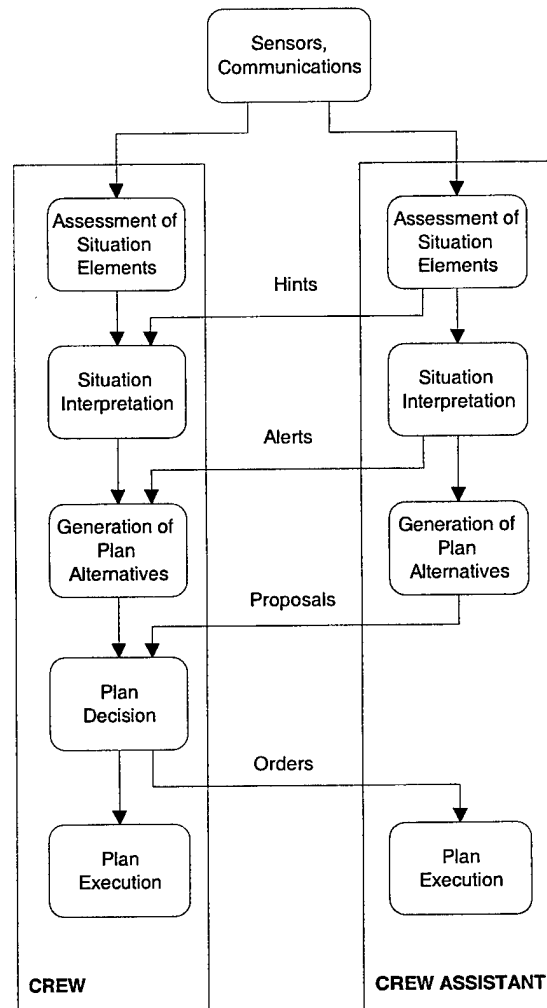


Figure 6 : Co-operation of Crew and EC

The next section will introduce the past and present efforts on electronic crewmembers for transport aircraft.

### 3. CREW ASSISTANT HISTORY AND STATE-OF-THE-ART

One of the first programs dealing with electronic crewmembers was the „Pilot's Associate“ of DARPA, which was targeted at assisting pilots in tactical combat

aircraft (see [ 7 ]). Similarly, the French „Copilote Electronique“ program [ 8 ] aims at knowledge-based pilot support in combat aircraft.

In the transport aircraft domain, efforts for knowledge-based pilot support started in 1986 with the ASPIO project [ 2 ] of the Universität der Bundeswehr München (UniBwM). ASPIO (Assistant for Single-Pilot IFR Operation) was characterised by the following features :

- Speech input and output as primary means of communication with the pilot
- Decision aid module for flight planning using fuzzy reasoning
- Representation of the pertinent aircraft operation knowledge by use of scripts and productions
- Monitoring of the actual pilot behaviour and alerting in case of errors

In 1990, the ASPIO system was successfully tested in a flight simulator.

Based on the lessons learned of the ASPIO project, a joint project of UniBwM and Daimler-Benz Aerospace was launched in 1991. Its goal was to develop a cockpit assistant system ( CASSY ) for intelligent crew support in commercial transport aircraft in order to ensure flight safety, reduce pilot workload and improve the flight plan efficiency (see [ 1 ] and [ 3 ]).

This was achieved by CASSY with the following basic functions :

- Assessment of the actual situation elements based on all available dynamic data of the aircraft and information uplinked by ATC
- Autonomous elaboration of flight plan and procedure proposals
- Autonomous evaluation of the actual flight situation based on extensive knowledge on the crew behaviour, crew error models and crew resources

The basic structure of CASSY is depicted in figure 7.

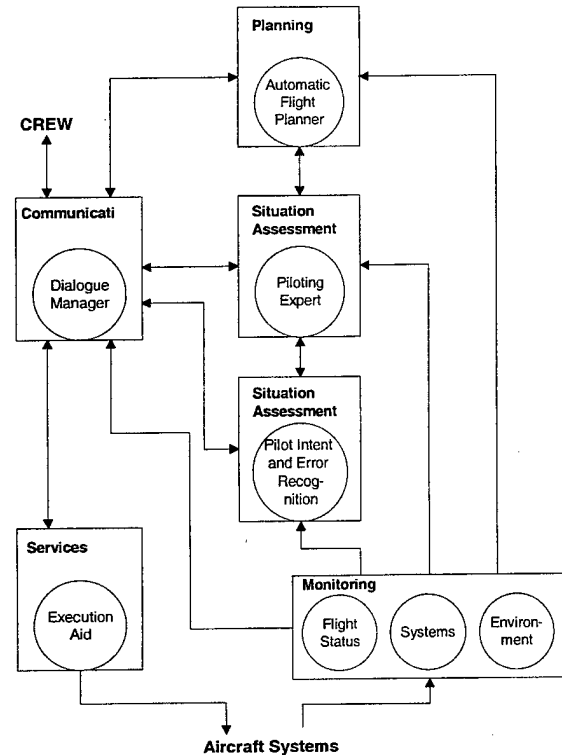


Figure 7 : Functional Blocks of CASSY

The functional blocks shown in figure 7 were realised as separate processes on a Silicon Graphics platform. The amount of source code finally reached more than 200.000 lines of „C“ code.

After an extensive test phase in flight simulators of UniBwM and Dasa, the CASSY prototype was integrated in the flying testbed ATTAS of the German Aerospace Research Establishment DLR at Braunschweig. The system was validated in 1994 by airline pilots in typical IFR flights to Hamburg, Hannover and Frankfurt (see [ 4 ]).

The CASSY flight trials confirmed that

- the use of speech input in the noisy flight deck environment is possible
- the knowledge based assessment of the pilot behaviour also works under severe real time conditions
- pilot errors can be detected and corrected before impacting the aircraft's safety
- inflight planning activities can be accelerated for the benefit of rapid reactions to a new situation
- user acceptance for this kind of support system is ensured

In 1993, parallel to the very successful CASSY activities, the German MOD started a research and technology development project called „Crew Assistant Military Aircraft“ (CAMA) [ 5 ] in order to investigate the use of an intelligent electronic crewmember in the military transport application. CAMA enhances the CASSY functions by :

- a tactical situation assessment
- a ground collision avoidance algorithm
- inclusion of the pilot's eye movements in the pilot behaviour assessment
- computer vision with respect to the outside world
- low level flight planning

A CAMA demonstrator is supposed to be validated in flight in 1999.

The overall success of the CASSY and CAMA projects leads to the question, how far the next logical step, the implementation as a commercial-off-the-shelf avionics product, is ahead.

Before an attempt to answer this question is made, the next section will try to describe the near-term air traffic scenario, that will significantly affect the flight deck environment and the airlines' equipment policy.

#### 4. FUTURE AIR TRAFFIC SCENARIO

The air traffic scenario will encounter significant changes during the next decade. Following ICAO's FANS concept („Future Air Navigation System“) (see [ 12 ]) the onboard equipment will need to be replaced in order to accommodate for the envisaged changes :

- Communications  
From today's VHF and HF voice communication, a transition to VHF / Mode S / SatCom datalink with voice backup is planned.
- Navigation  
The navigation presently is based on radio navigation (NDB; VOR; DME) for enroute and terminal operations and ILS for precision approach and landing. This will change completely towards satellite-based navigation enroute (GPS / GLONASS) and MLS/GPS precision approach and landing.
- Surveillance  
The present surveillance system of primary / secondary radar and voice position reports will be replaced by a mixture of ADS (Automatic Dependent Surveillance) and secondary radar (Modes A/C/S).
- Air Traffic Management (ATM)  
The current air traffic system with its fixed route structure and separation control by air traffic con-

trollers will change to a flexible airspace use, where the separation responsibility will more and more be transferred to the aircraft (the so-called „Free Flight“ concept).

The ATM system operation within the long-term FANS concept (for details please refer to [ 9 ]) will involve the type of airspace, and the associated airspace boundaries, being designated dynamically (i.e. designated according to the actual traffic demand for the relevant period of time). Direct routing will be used for all en-route flying (no fixed route structure). Two types of airspace will be available:

##### Autonomous Airspace:

- only used in low/medium traffic density situations
- only available to suitably equipped aircraft
- ground ATM system ensures that traffic density does not exceed a safe level
- aircraft follow free flight trajectories
- conflict detection and resolution using on-board system (Super Traffic Alert and Collision Avoidance System (Super TCAS))
- independent safety back-up for collision avoidance provided by TCAS
- all trajectories and modifications downlinked to the ground ATM system to enable overall system monitoring

##### Controlled Airspace:

- will apply to all high traffic density situations
- ground ATM system ensures that traffic density does not exceed a safe level
- ground ATM system responsible for conflict detection, resolution, system monitoring
- conflict resolution instructions uplinked to relevant aircraft (resolution responsibility can be delegated to aircraft equipped for autonomous operation)
- majority of aircraft operating to 4D contracts negotiated over data link
- less well-equipped aircraft given strategic instructions over data link
- tactical control by R/T will only be used in failure/emergency situations
- operational strategy ensures that best equipped aircraft receive the best service (i.e. get minimum disturbance from their ideal flight path)

This future ATM situation will require onboard equipment with the following capabilities:

- 4D trajectory generation, taking into account pilot and Airline Operation Control (AOC) requirements, airspace restrictions, any ground ATM imposed

constraints, and also any conflict resolution requirements (for autonomous operation)

- 4D guidance within bubble of airspace allocated by ground ATM system, or along ideal trajectory in Autonomous airspace
- contract negotiation with ground ATM system over data link
- performance monitoring relative to Required Navigation Performance (RNP) for current airspace
- Precision Position Determination - using GNSS (high-integrity civil system)
- Data Link using Satellite, VHF and Mode S links to provide two-way link between:
  - Pilot/Controller - for contract negotiation, strategic instructions, meteo forecasts
  - Aircraft/ATM system - for ADS etc. (no direct controller/pilot involvement)
  - Aircraft/AOC - for airline operational, maintenance etc. purposes
  - Aircraft/Aircraft - for autonomous conflict detection and resolution
- Conflict Detection and Resolution - a Super TCAS providing medium-term (5-10 minutes) capability in autonomous airspace
- Collision Avoidance - TCAS to provide an independent short-term safety backup
- Cockpit Human-Machine Interface - displays and inputting capabilities to ensure adequate crew monitoring and control of FMS, Data Link, etc. in a 4D negotiated contract environment, and suitable traffic information displays for operation in autonomous airspace

While some of the CNS/ATM feature described above are to be seen on a long-term scale, there are a lot of „first steps“ in the near future that force airlines (see [ 6 ]) and other commercial aircraft operators to invest heavily in new equipment, that provides :

- Reduced Vertical Separation Minima (RVSM),
- 8.33 kHz VHF channel separation,
- Traffic Collision Avoidance,
- VHF / Mode S / SatCom Datalink,
- Basic Area Navigation (B-RNAV),
- MLS / GPS approach and landing .

This impressive shopping list indicates that airline and commercial aircraft operators are under extreme investment pressure for new avionics equipment in order to be prepared for the new air traffic system.

It is quite obvious, that under those circumstances the priority of electronic crewmembers to support the pilots is very low.

Or, to put it bluntly, the airlines and commercial aircraft operators presently have other things to care for than an electronic crewmember that just increases flight safety („We're safe anyway“) and decreases pilot workload („What are they being paid for ?“).

## 5. CONCLUSION

The dilemma is quite obvious. On one hand the need for intelligent pilot support, implemented through an electronic crewmember, is recognised and the technological maturity of the proposed solutions, such as CASSY, has been demonstrated in flight. On the other hand, airlines and other commercial operators consider EC's as „nice-to-have“ for the time being . Consequently they are not prepared to invest in EC products today. And, to be honest, one has to admit that it wouldn't be a small investment. Just think of the non-recurring costs for a software with more than 200 kLOCs if they were developed according to the certification standards for flight essential systems.

The way ahead might therefore be :

1. Introduce the basic EC functions step-by-step in commercial avionics, e.g the flight management system, without increasing the prices. This might be the „winning point“ for the customer and therefore pay off.
2. Focus on military transport applications, where the technological challenges are even higher and the economical pressure on the operator are lower. Advance thereby the state-of-the-art and try to have a commercial EC as spin-off.

To conclude and to answer the question of the title : the authors of this paper are deeply convinced that on some day in the future the human crewmembers will be welcomed on their flight deck by an electronic crewmember.

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# GENERIC ARCHITECTURE FOR A PILOT ASSISTANT SYSTEM

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## SUMMARY

This article describes a generic software architecture for the interaction between the modules of a pilot assistant system based on shared memory blocks and a central communication control module. The architecture does not depend on the number or functionality of the modules and is therefore largely independent of a specific application. The consistency of shared data is ensured with read and write locking. Other central features are the ability to easily integrate additional modules at runtime and the special consideration of any-time-algorithms to support planning modules in a real time environment. The interaction of the modules and their functionality are strictly separated to enhance the maintainability and to simplify the implementation of modules as well as to improve the reusability of the architecture for different assistant systems.

## 1. INTRODUCTION

The Institute of Flight Guidance of the German Aerospace Research Establishment (DLR) in Braunschweig is currently developing a prototype of an intelligent pilot assistant system to support the pilot in a Free Flight scenario [1, 2]. This system features new functions for autonomous separation assurance, including monitoring of air traffic and trajectory planning.

Currently the technical possibilities, as well as the potential benefits and dangers of Free Flight are still being investigated and a clearly defined Free Flight scenario does not yet exist. The exact behaviour of the assistant system, however, can only be defined once the Free Flight scenario has been laid out with sufficient detail. Hence the architecture of the assistant system must be highly flexible, so that the impact of revised design decisions will be limited.

Similar to current experimental pilot assistant systems (e.g. CAMA, CASSY [3]), the basic functions of the Free Flight assistant system will be a human machine interface (HMI), monitoring (surrounding traffic and on-board systems), situation assessment (conflict prediction, system diagnosis) and trajectory planning, as shown in figure 1. In a specific assistant system the function block templates are substituted by one or more function modules. The difference between a Free Flight assistant system and previous systems is not necessarily apparent in all basic functions, for example system diagnosis components can still be used in the Free Flight assistant system, since the characteristics of the aircraft have not changed. There will, however, still be some work required for integration and

adaptation of such functions. Since the Free Flight concept itself is still a research issue it is intended to build a prototype first, which will have functions that probably do not differ from the final system.

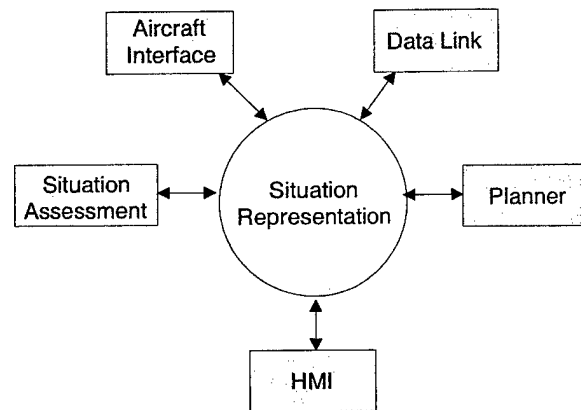


Figure 1: Basic functions of a pilot assistant system.

For these reasons we are developing a generic interaction scheme (software architecture) for the assistant system, which supports the direct inclusion of function modules from other systems. Modules which have been tested in the prototype can then be integrated into the final system without much effort. The complete interaction between all modules is the main part of the generic design. Fixing this interaction by design does not only enable reusing modules in different assistant systems, but it also simplifies the maintenance of such systems. In the development of new modules one can concentrate on the functionality, since the entire interaction within the assistant system has been developed and already tested. As far as message flow and data interchange is concerned, there is no necessity to distinguish between different kinds of function modules, as for example between a traffic monitor and a free flight planner. Therefore, in the following we will speak of general function modules and do not have specific modules in mind.

Aside from the requirements mentioned the generic architecture must meet some more criteria:

- The architecture must support the inclusion of new function modules (e.g. weather monitor), this should be possible even at runtime.
- Modelling system behaviour is achieved by modelling module interaction. In a generic

architecture the interaction must not explicitly include specific modules, since replacing a module could otherwise require a redesign of the interaction.

- Function modules can be triggered by event and/or periodically.
- The use of planners in a real time environment places additional requirements on the interaction: In general there will be time limits for planning tasks. It must be also possible to involve changes of the environment in the current planning process. The architecture must allow the use of such complex modules without constraining their functionality.

In this paper we are presenting one possible variant of a generic, object oriented architecture for module interaction that satisfies these requirements. The use of this architecture is by no means limited to pilot assistant systems, it could be used for any system, which functions are divided into several modules.

This paper will not treat the subject of object oriented software development. For the important topics of inheritance and polymorphy the reader is referred to the literature, e.g. [4,5].

## 2. MODULE INTERACTION AND SITUATION REPRESENTATION

From an implementational point of view it is desirable to divide the system into separate modules (processes). This can significantly ease the development of functions and also maintenance of the system. There are many possibilities for the interaction between such modules, e.g. one could think of a direct communication between all modules. Because the modules run concurrently it is hard to get a clear picture of all interaction that takes place over time, and therefore the integration of a new module into an existing system is not only expensive but susceptible to errors and inconsistencies. Moreover, using direct communication one needs to know about all participating modules and probably has to make changes to existing modules, too.

However, a module must not know about the existence of other modules in the system and it must not make assumptions about them. This would limit its future use in another system and also a runtime reconfiguration of the assistant system. Hence an important feature of a module is that it does not know how its output is processed by other modules and also where its input is coming from. In order to combine a number of modules to a complete system a central module is required, which we call Module Manager (MM). This is the only module that function modules can assume to exist and during initialisation each function module must register with the MM. This makes all active modules known to the MM. All data that shall be transferred between modules are collected in the central situation representation, which will be called Data Pool

(DP) in the following. In order to be able to follow events in the system without making assumptions about other modules, they can bind themselves to certain data objects within the DP. In this case the module will be notified whenever the object changes and can respond accordingly. Instead of an explicit definition of the interaction between modules, this interaction is implicitly defined via data objects:

The system diagnosis module monitors the data from the aircraft interface and in case of a failure generates a diagnosis and perhaps corrected performance data. The planner reacts to changes of the performance data and trajectories of other aircraft, it checks whether the active trajectory can still be flown and suggests an alternate trajectory. Finally the HMI informs the pilot of the failure and that an alternate trajectory is suggested by the system.

In this simple example data objects are Aircraft-Interface-Data, Diagnostic-Result, Performance-Data, Other-Trajectories, and Suggested-Alternate. The modules register with the MM informing the MM about which objects they will read (e.g. planner will read Performance-Data and Other-Trajectories). Although the MM does not know about the functions of the modules, it knows which data objects are read by each module. The MM will notify all registered readers of an object in case the object changes. In this way the planner will be notified of the changed performance data in the above example. Hence the use of a module is tied to its input and output data which are defined in the module implementation. It is not important to the planning module whether the performance data are generated by the diagnosis module or by an additional module that may be added at a later time.

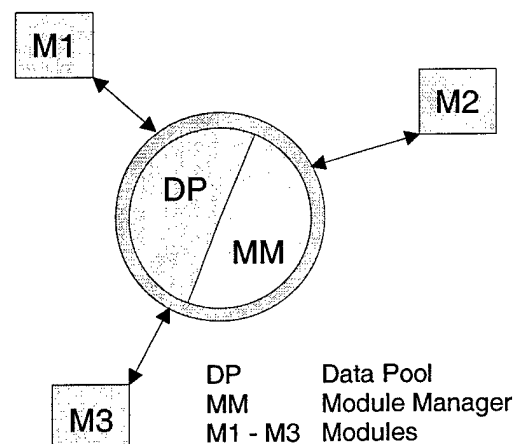


Figure 2: Only DP and MM are guaranteed to exist in the generic architecture for module interaction.



Hence the core of the assistant system consists of the Module Manager and Data Pool. Any function module can rely on their existence in any system (Figure 2). Aside from providing read and write locking mechanisms the DP maintains a list of readers for each data object. In the example the planner and the HMI are readers of the Performance-Data, while the diagnosis module is its writer. The MM uses this information to inform registered modules via messages about changes of data objects. This functionality has been realised using an object oriented programming language with inheritance and encapsulation of data. Hence access violations can be recognised during compile time already. Additional control mechanisms are achieved by performing consistency checks during system initialisation. Aside from the event triggered notification described above, modules can also be triggered periodically.

The Module Manager offers additional benefits for the module interaction. All messages and information are passing through this central modul, and therefore mechanism for load distribution or deactivation of modules, which cannot contribute significantly to the solution in a critical situation, can be easily implemented. In addition the system behaviour (e.g. message flow) becomes more transparent, when it can be explained by observing just one module rather than all modules simultaneously. This also enables proving a specific system behaviour despite of using concurrent modules.

Even though Module Manager and Data Pool are termed modules in this paper, they may not be implemented by individual processes. It is also possible to distribute their functionality to the individual function modules of the assistant system.

### 3. MESSAGES

In the previous chapter messages have been mentioned already in connection with the functionality of the Data Pool. In case a data object changes, the DP sends messages to all modules that are readers of this object. It is, however, not always desirable to send such messages after each write operation, since then other modules might have to spend much time with reactions to update-messages even though the data object may still change several times over a very short period of time. For example, a planning module may be planning an avoidance trajectory to solve a conflict that is expected in eight minutes by continuously improving an initial trajectory. The other modules should not be informed of every update to this trajectory, it is sufficient if they are informed once the planning is completed. Therefore special access operations are provided by the DP which suppress messages to other modules. Depending on the situation a module can then use the appropriate access operation.

The use of write operations without messages to other modules, however, causes another problem. Considering the example above there will be a point in time at which the planning must have finished, since otherwise the conflict cannot be avoided any more. In general complex planning tasks are NP-complete, i.e. the time required to compute an optimal plan depends exponentially on the number of planning parameters, e.g. the number of other aircraft. Therefore it cannot be guaranteed that the planner has completed the next improvement to the plan within the remaining time so that it may not be able to issue an update-message any more.

This problem can be solved by adding timers to update-messages. Upon expiration of the timer the message will be sent to the other modules. This assures that the planning result at the moment the timer expires is available to the other modules, even when the planner itself would be caught in an endless loop.

Based on the above a message consists of the following:

- Sender (e.g. System Diagnostics)
- Receiver (e.g. Module Manager)
- Message type (e.g. write operation)
- Data object (e.g. Performance-Data)
- Time at which the message should be sent

(Normally messages will be sent immediately, i.e. the default timer value is "Now".)

Among others our system architecture uses the following message types:

- Log\_Read: Register as reader of a data object,
- Unlog\_Read: Cancel registration as reader,
- DO\_Update: data object has been updated,
- Continue: continue previously interrupted task of a module,
- Update\_Timer: update timer values of all messages referring to the same data object,
- Stop: Terminate process.

### 4. IMPLEMENTATION

The core of the assistant system is implemented without any knowledge about function modules to be connected later on. The implementation comprises realisation of the MM and DP as well as a template for function modules. This template contains placeholders for the actual functions of the modules, while the part necessary for the interaction with other modules is completely implemented. Hence a complete module

that is immediately usable in the assistant system can be built rapidly by filling the placeholders with the required functions. Using the module template guarantees that the module complies with the communication rules and therefore can also be used in different assistant systems. The prerequisites for this approach are provided by using an object oriented programming language (Use of abstract base classes and polymorphism [4]). Hence the architecture is generic concerning the communication between modules, which was designed for arbitrary assistant systems. In the following section the interaction between modules is specified in more detail.

### Function Modules

For each module a list of messages is managed. The previous chapters then imply the following algorithm for a function module, which is shown in figure 3.

Upon initialisation a module will send a Log\_read message for each data object that it needs to read and then waits for incoming messages. These are processed one after the other. Each module will have a function "do\_update" to process DO\_Update messages. For example the planner might include "do\_update" functions for the performance data. The "do\_update" function is meant to perform only administrative tasks like checking which action must take place. The actual module task is done within the "process\_work" function, after all DO\_Update messages have been processed. The module will make changes to the Data Pool, which will then lead to DO\_Update messages to other modules, only from within the "process\_work" function. Modules, which work periodically, also include a "send\_delayed\_continue" function, which sends a Continue message with a timer value to the Module Manager. The MM will then send a Continue message back to the module when the timer expires.

```

send_log_read()
Repeat
    While message list empty
        Wait for next message

    For all messages M in list
        Read message M
        Select type
            DO_Update :
                Remove all
                DO_Update for data object
                data object of message
                do_update() for
                Continue:
                Remove all Continue
                messages
            process_work ()
            send_delayed_continue()
until Stop message
send_unlog_read()

```

Figure 3: Algorithm of a function module.

In general the "do\_update" functions require little computation time. This is, however, not true for the "process\_work" function. While the possibility to set timers at the beginning of "process\_work" assures that other modules receive a DO\_Update message in time, another problem arises since the module is unable to process incoming messages itself until "process\_work" returns. For example the result of a planner may be completely useless after a single change in the environment. In this case an immediate termination of the planning process would be appropriate. On the other hand a change in the environment may have no influence on the planning result, so that restarting the planner would lead to the same result. Only the planner itself can judge whether a restart is appropriate or not, since no other module has the required information about the internal state of the planner.

Therefore it is necessary to provide the possibility to process arriving messages within the "process\_work" function. This can be achieved by replacing the "process\_work, send delayed continue" part in the above algorithm (figure 3) with the algorithm in figure

```

Repeat
    done := process_work ()
    If done
        send_delayed_continue ()
        Send Message(S,MM,Update_Timer,-,Now)
until (done or message list not empty)

```

4.

Figure 4: Modification of algorithm to handle new messages while process is working.

With this modification it can be controlled by the implementation of the "process\_work" function, at which points the module can process incoming messages. If the "process\_work" function of a module requires only little computation time, it will always return "true" (ready). In other cases the function will perform only some part of its calculations and then return "false" (not ready). The module can then process incoming messages and "process\_work" can resume. All DO\_Update messages will be set to a timer value of "Now" by the Update\_Timer message once "process\_work" finishes.

All modules of the assistant system follow the same interaction algorithm. A complete module can be built by implementing the "send\_log\_read", "send\_delayed\_continue", "do\_update" and "process\_work" functions.

### Data Pool

The DP is an active part of the interaction. It provides write locks, which send messages to the MM when

```

Repeat
  While message list is empty and time of first
    element of TL is not
  reached
    Wait for next message or time

    For all M in TL with time "Now"
      Insert M into list of messages
      Remove M from TL

      Get M from list of messages

      If      (Time later than "Now") and
              (Type not equal
Update_Timer)
        Insert M into TL
      else
        select Type
          case Update_Timer:
            For all messages for same
object
              Remove from TL or list of messages
              Replace time
              case Log_Read:
                Insert sender in
list of readers
              case DO_Update:
                For all readers R
of data object
                  Send
DO_Update message to R
                  case Continue:
                    Send Continue Message to
sender
                  case Unlog_Read:
                    Remove sender
from list of readers
until Stop message

```

requested by the function modules. Write locks can send messages immediately after the object has been modified, messages can be delayed (message with timer), or no message is sent at all. It is up to each module to select the appropriate write lock based on the relevance of the object modification in the current situation and context.

### Module Manager

In addition to the list of messages to be processed the Module Manager also maintains the timer-message list TL, which is sorted by timer value. The algorithm, shown in figure 5, applies.

The Module Manager waits for new messages or is activated, when one of the timers expires. In this case all messages, whose timer has also expired are inserted into the list of messages. Then all messages are processed in order. If a message lies in the future, this message includes a timer and is therefore inserted into the timer list TL. The only exception is the Update\_Timer message. It is always

processed immediately. The timer value indicates how the corresponding timer-messages should be modified. (In general the timer value will be set to "Now", since the "process\_work" function of the sender is done.)

To trigger modules periodically, timers can be used to send delayed Continue messages. The MM returns Continue messages directly to the sender. Therefore, in the function module function „send\_delayed\_continue“ a module can use delayed Continue messages to trigger itself after the timer has expired.

Figure 5: Module Manager algorithm.

### 5. SUMMARY AND OUTLOOK

Growing demands on the aircrew due to increasing traffic volume or changes in ATM structures lead to the requirement for pilot assistant systems with new functionality. This will, however, make not all components of current systems obsolete (monitoring, situation assessment, planning, HMI), so that it is advisable to borrow functions for new systems from current systems.

In this paper a software architecture for a generic interaction scheme has been presented, which provides a clear separation between module interaction and module functionality in a pilot assistant system. In addition to simplify testing and maintenance of individual modules this separation also reduces the development effort for new assistant systems. The implementation of the module interaction serves as a common basis for various assistant systems, which on the one hand allows to integrate existing modules into new systems very easily, and on the other hand reduces the effort for the development of new modules by concentrating on their functionality. The dependencies between the modules are modelled via their shared data objects, modules declare themselves as reader or writer of these objects during initialisation. If a data object is used by several modules, the reader modules are implicitly dependent on the writer module. The mechanisms for interaction are designed in such a way that special requirements of real time systems (e.g. any-time-planner) are taken into account. Future enhancements to the interaction are also simplified, since they are implemented at one central location rather than in each individual module. This is a prerequisite for the desired longevity of the concept.

The core system is currently being developed and will be implemented in a pilot assistant prototype. Building on this prototype the flexibility of the concept will be utilised to build a final assistant system for a Free Flight scenario. At that point in time the core system will have accumulated a number of testing hours in the prototype, so that a reduced effort for the development

of the interaction is expected, even though the system is growing in complexity.

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Hazard Monitor:  
A Pilot Decision Aiding System  
Executive Brief

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## Overview

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## What is Hazard Monitor?

Hazard Monitor (HM) is a knowledge-based system that alerts human operators to discrepancies between actual and expected system states in a *human-centered* and *context-sensitive* manner before the adverse consequences of the discrepancies become unavoidable.

HM uses existing alerting mechanisms to notify pilots of problems in time to take corrective actions, if the pilots choose to do so. It is a "discrepancy highlighter."

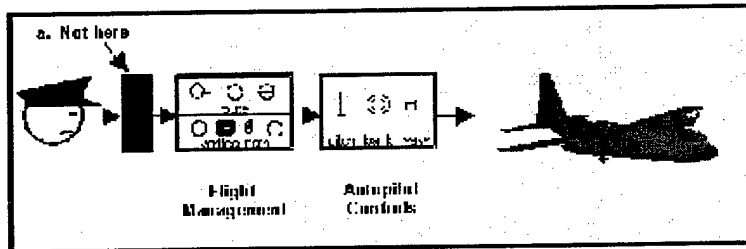
Think of HM as a situation awareness enhancer.

*Human-centered and context-sensitive* means - take all available data and examine them from the human's goal-oriented and hazard-avoidance perspective. Therefore, the severity of, and proximity to, the adverse consequences are factors in determining the alerts and their level (warning, caution, advisory).

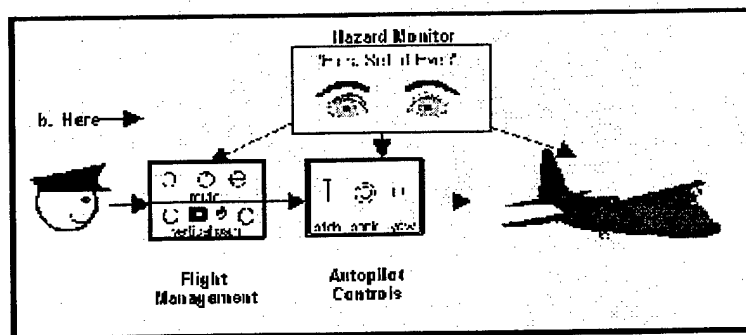
## Why is Hazard Monitor Needed?

- Complex systems and environments, opaque interfaces and over-automation make errors likely.

- Accidents do not typically occur due to single, isolated errors. They occur due to a "chain of events" that the human operator does not detect or does not fully appreciate (level 1: detection, level 2: comprehension and level 3: projection - SA problems).
- Traditional error strategies (structured design, ergonomics, personnel selection, traditional training and automation) have reached limits of effectiveness.
- Accidents are not the only problem. System inefficiencies result from these problems, much more often than do accidents.
- Blaming pilots is not the answer! Helping pilots avoid consequences is part of the answer.



There is a questionable advantage to the introduction of more technology as "intermediary". This only distances the operator from the system which is to be controlled and monitored.



Instead, HM is designed as an associate system pilot aid, providing an "extra set of eyes" to the crew. Its purpose is to support pilot roles.

### Brief Hazard Monitor History

- Pilot's Associate (PA) - DARPA/USAF 1985-1992 (USAF contract F33615-85-C-3804)
  - AI used to enhance fighter pilot SA and improve mission effectiveness.
  - HM was called "Error Monitor". It was one small part of the Pilot Vehicle Interface (PVI), which was 1/5<sup>th</sup> of PA.
- NASA SBIR - NASA-Langley 1992-1995 (NASA Contract NAS1-20210)
  - Error Monitor used to help airline pilots deal with complex FMS interactions.
  - Integrated with Boeing 747-400 FMS made by Honeywell. POS INIT errors, waypoint errors, descent and approach hazards.
  - The name Error Monitor (EM) was changed to Hazard Monitor (HM) to remove the notion of blame.
- USAF SBIR - Wright Lab 1994-1997 (USAF contract F33615-95-C-3611)
  - A new arbitration and presentation management capability was added to handle subtle

notification inter-dependencies: duplicates, priorities, conflicts, abstraction.

- Networks implemented included: emergency and normal descent, safe airspeed, safe cabin altitude, altimeter setting, normal approach, and go-around hazard networks for military transport.
- USAF SBIR - Armstrong Lab 1997 (USAF contract F41624-97-C-5027)
  - The HM design was enhanced to support intelligent tutoring: real-time aiding, and post-flight debriefing.

### **Which types of problems does HM help resolve?**

- There are common problem characteristics:
  - Evolving situation with subtle cues
  - Time for human to recognize and act to avoid bad consequences
  - Advantage to consistency checking
  - Utility in detection enhancement
  - FAR, SOP compliance especially during goal-oriented activity For example, "approach gates" compliance
- HM provides a general solution to a range of problems, not a point solution to specific problems.
- Pilot technique accommodated
  - We explicitly acknowledge the need for pilot authority & creativity
  - Allow the operator to choose and implement a strategy
  - Pilot knows what to do when a potential problem is identified
- Assumes sufficient data available electronically
  - Airplane data bus, ATC data-link, NAV and terrain data bases

### **Which types of problems does HM not help resolve?**

- Specific problems already being addressed by very capable systems
  - CFIT (GPWS), mid-air collisions (TCAS)
- Catastrophic events
  - Subsystem failures; e.g., fan blade failure
  - Weather; e.g., lightning strikes
- Communication problems
  - ATC, CRM
- Subsystem diagnoses
  - We do not want to replicate built-in test equipment
- Maintenance, repair or overhaul (MRO) discrepancies

## How Hazard Monitor Works

Pilot-Centered monitoring & presentation is made possible through Persistence and Context-Sensitivity

- Persistence
  - The pilots are notified of discrepant states leading to potential hazards upon detection and for as long as monitoring is performed.
  - As the context changes (increasing proximity or severity of the consequences), HM re-sends the alert, with an increased severity level if appropriate.
  - Context - Sensitivity is defined by the elements which comprise the networks:
  - *Expectation Networks* describe goal-directed activities and procedures which are monitored.
  - *Initiators* describe the context (conditions) for beginning to monitor an activity (example: inside initial approach fix).
  - *Terminators* describe the context for ending monitoring due to: goal achievement (ex. landed) or abandonment (ex. go-around).
  - *Situation Nodes* describe the sub-contexts within activities that are meaningful to the pilot: locations where new states should be monitored; irrelevant states no longer monitored; convenient location to adjust severity of notification if appropriate. situation nodes represent the current context up to the point where right-hand node becomes new current context. ( there is implicit coverage of the context / state space between nodes)
  - *Expectations* describe the aircraft states and their expected ranges within the context of the activity. Failed expectations trigger candidate notifications for presentation to the pilots.

## Expectation Network Structure

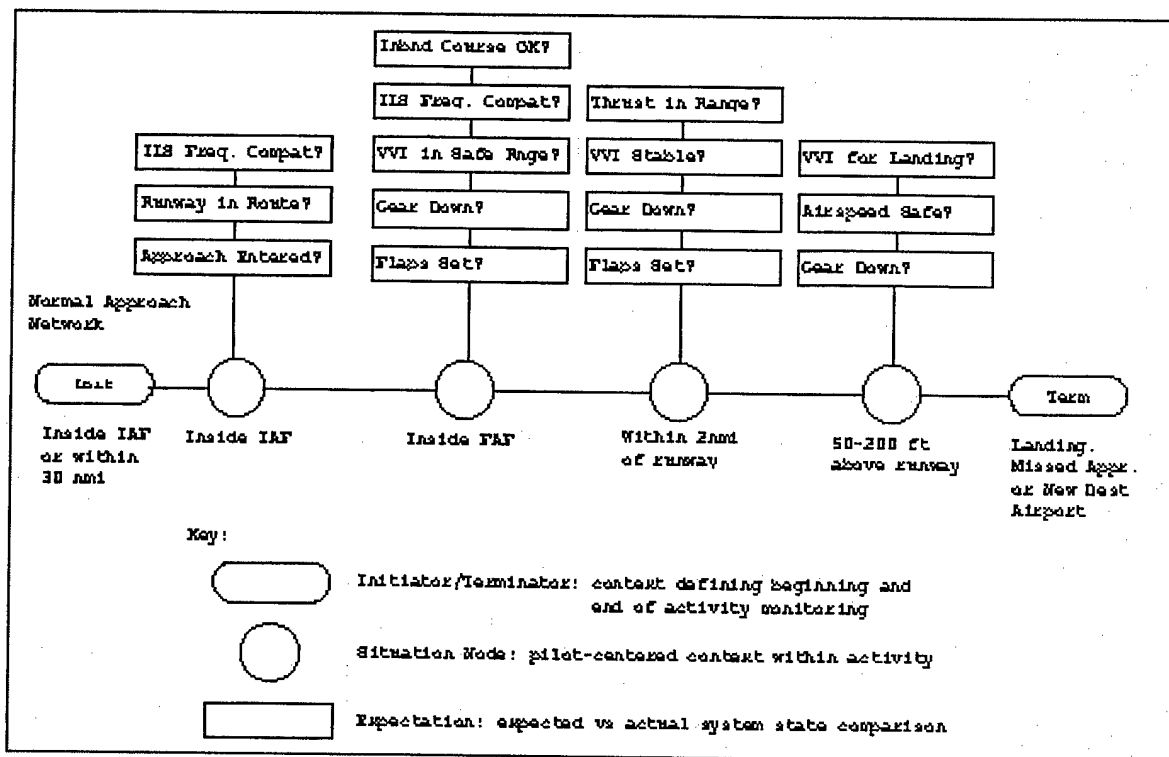
The Hazard networks (also called expectation networks) provide the scaffolding for the efficient encoding of domain expertise. Each network represents a normative model for an associated activity or procedure.

The network does not implement an electronic checklist. HM and the domain knowledge are engineered so that the system remains silent unless pilot is late. This accommodates pilot technique.

The structure supports incremental knowledge refinement and the addition of new knowledge.

All sub-contexts within an activity or procedure need not be modeled, only those where a domain expert indicates significant discrepancies should be brought to the attention of the crew.





## Sample Expectation Networks

While we've concentrated on hazard prone descent and approach phases of flight, HM can be configured with networks relevant to other flight phases. In addition, HM can accomplish monitoring for safe configuration and safe limits during all phases of flight.

### 1. Normal descent network

- Runway in route
- MCP altitude set
- VVI/descent rate
- Configuration
- Thrust (with/without icing)

### 2. Safe airspeed network

- Gear over-speed
- Flaps over-speed
- Airspeed exceeds  $V_{MO}$
- Airspeed > 250 below 10,000'
- Airspeed less than  $V_{MIN}$
- Airspeed fault (pitot tube icing)

### 3. Safe cabin altitude network

- Cabin altitude exceeds 10,000
- Cabin altitude exceeds 14,000
- Cabin altitude exceeds 25,000

### 4. Emergency descent network

- VVI/descent rate
- Configuration

### 5. Descent altimeter setting network

- Altimeter still set at 29.92
- AGL and MSL disagreement

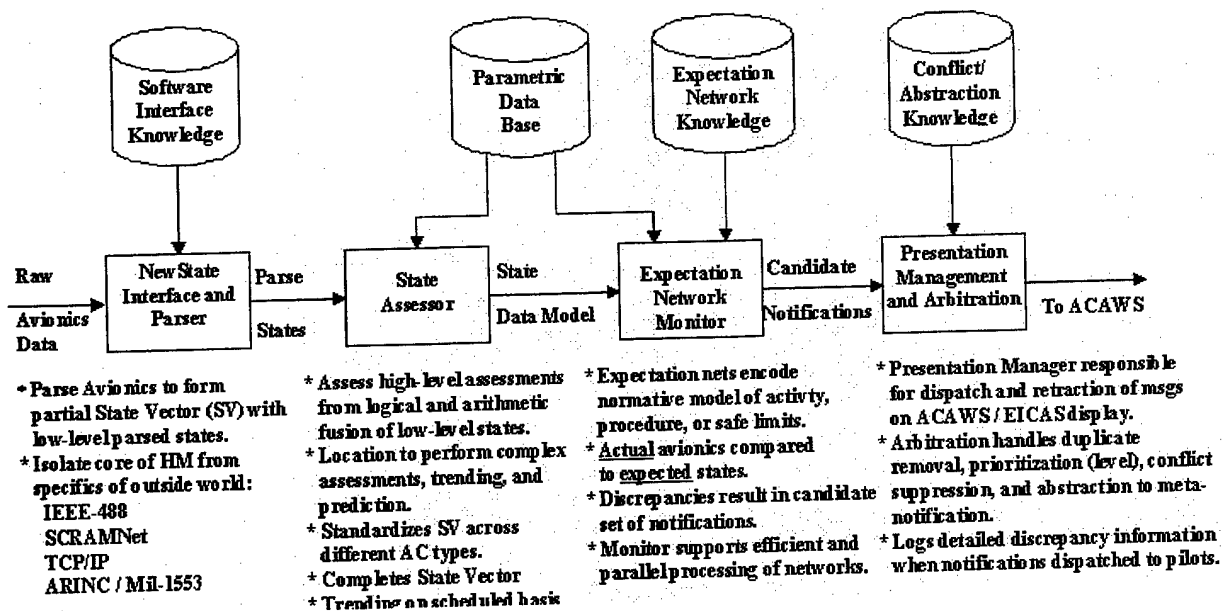
### 6. Normal approach network

- Approach, runway entered
- ILS frequency entered
- Flaps, gear set
- Airspeed
- Inbound course
- VVI
- If multiple discrepancies, "Unstable Approach"

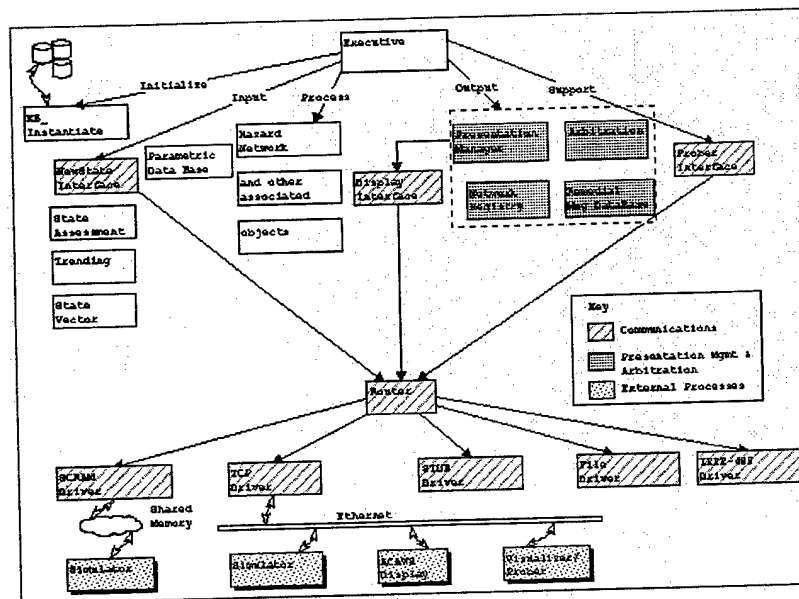
### 7. Go around network

- Go around thrust
- Go around airspeed
- Go around VVI
- Go around pitch
- If multiple discrepancies, "Sink Warning"

## Hazard Monitor Architecture: Input / Processing / Output



## Hazard Monitor Architecture: Class / Object Diagram



Domain knowledge is "instantiated" in memory during system initialization.

Input, Process, Output and Support phases of processing proceed in a round-robin fashion.

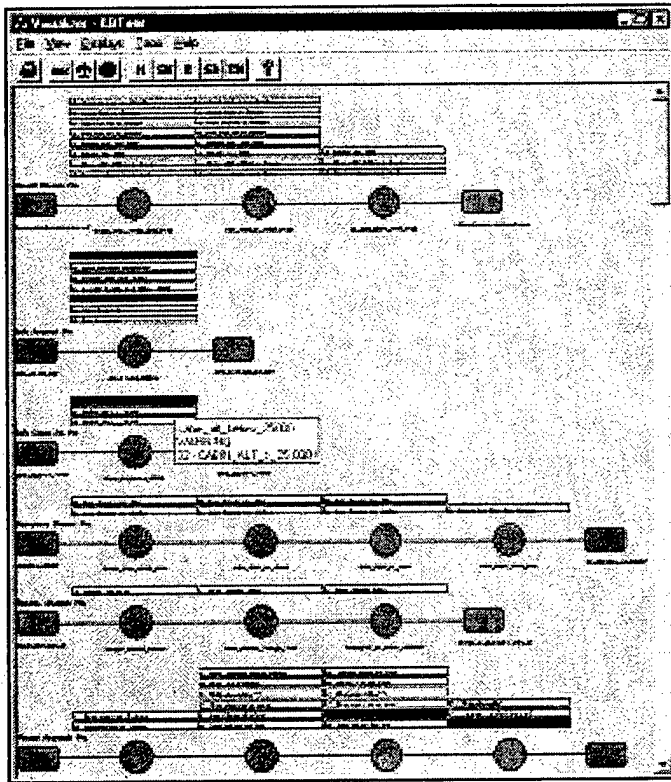
Interface objects call upon intermediate Router and Driver objects to communicate with external processes.

The State Data object represents the state vector accessible by the rest of the architecture.

Presentation Manager and Arbitration objects log notifications, and reduces the set of alerts presented to the output device (ACAWS, EICAS).

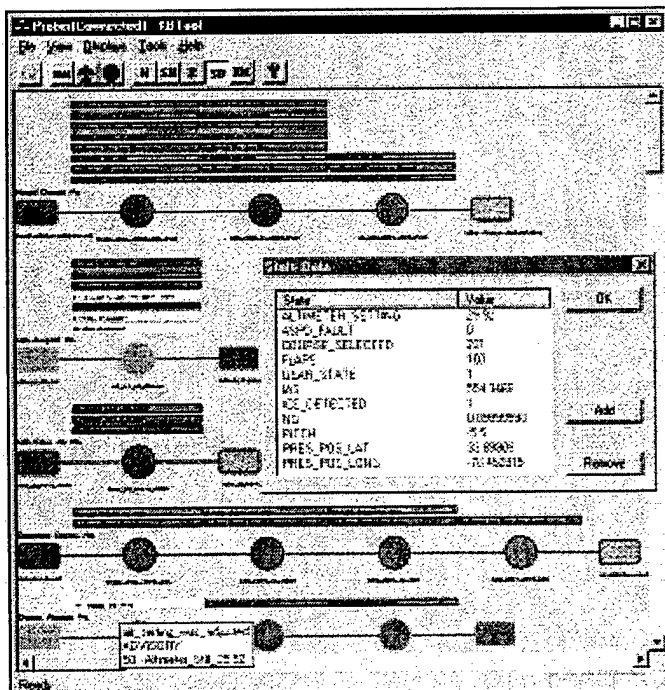
## Hazard Monitor System Tools

### Validator and Visualizer



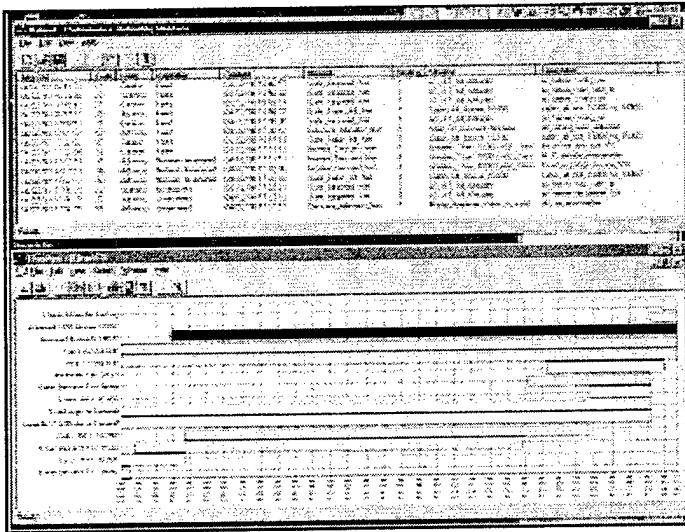
Parses Knowledge Base files comprising expectation networks. Performs syntax-checking and error reporting. Displays a graphical representation of the hazard networks. A mechanism to examine, communicate, and produce hard-copy documentation of the configuration of the domain expertise.

### Prober



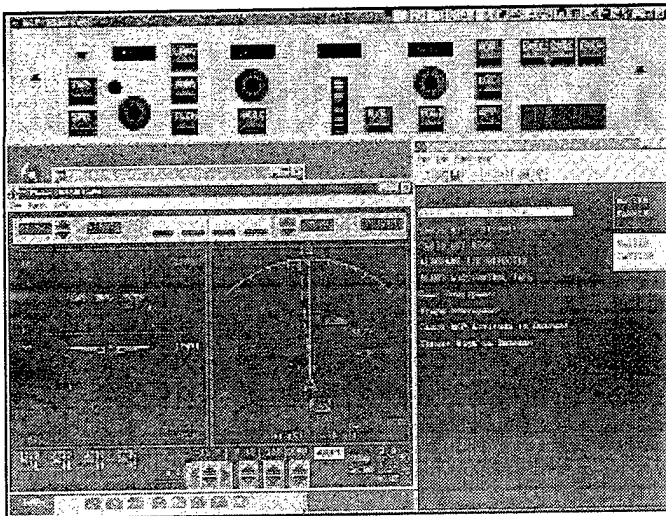
An extension of the Visualizer tool. Reveals real-time processing behaviors of Hazard Monitor for inspection during configuration testing. Updates graphical representation of nets via color highlighting and flood fills based on truth-value of network elements. Provides mechanism to selectively examine state vector contents in real time.

## Debrief



Visualizes the contents of the detailed notification log created by Presentation Manager object. Log file written as HM monitors for discrepancies leading to hazardous consequences and updates the display device. Log includes as a minimum, the following data: time message dispatched to display, time retracted, reason retracted, alert severity level, associated context (network, situation, expectation). List format supports sorting on column (ascending/descending) – notification log easily imported into commercial spreadsheet packages. Graphical format depicts log information about time-line or potentially other relevant taxonomies (aviate, navigate, communicate, manage systems, safety, SOP, performance, economy, network, situation).

## Simulation with CAWS display



Pictured here is a modified version of a desk-top simulator program which provides a means to test HM configurations against "canned" scenarios or in an unscripted manner under the Windows NT operating system.

A generic CAWS display is used to visualize the output of HM. It provides priority sorted list support for warning, caution, and advisory notification. A message "explain" capability is also available by double clicking on the message of interest.

## HM Technology Differentiators

- Pilot-centered, context-sensitive monitoring: efficiently accommodates pilot technique and authority. Silent unless certain that pilot late.
- Domain-level configuration: level of specificity / abstraction appropriate for customer programmability requirements. The objects manipulated are mnemonically familiar to domain experts.

- Object-oriented design: networks encapsulate functionality and support addition of new attributes; nets support incremental KB development and refinement; elements of architecture can be replaced with minimal impact to the rest of the system.
- KBS separation of code and data: data is configured by end-user; code implementing functionality developed and certified once; end-user would pick and choose from a collection of certified elements; parametric data store provides a means to easily adjust limits, dead-bands, and other comparison values.
- Resource-friendly processing: monitoring is conducted only in the context in which associated activities are being pursued; networks could support parallel processing; complex trending assessments scheduled at configured rates.
- Tool set supports knowledge life-cycle: Validator / Visualizer for configuration, Prober for dynamic processing behaviors, Debriefier for post-flight discrepancy analysis.
- Capable of multi-sensor data fusion; not single sensor / single alert technology; framework for de-confliction of notifications and abstraction to meta-level notifications.
- Flexible logging and recording of notification events linked to state vector snapshots. Used by debriefing tools for reflection on performance to uncover gulfs in proficiency / technique, poor SOP, or loss of SA.
- Multi-use: military and commercial real-time piloting aid applications, intelligent tutoring, post-flight FOQA analysis.

## **Possible Applications**

### **General Pilot Aiding**

- Initial focus would be on non-essential monitoring and alerting in a focused application: attitude, AS, trim run-away, flaps, gear, thrust, fuel.
- Plan would be to validate HM, certify it, and install it.
- Fly pilots with and without HM in high-fidelity simulator environment to measure performance differences.
- Questions to be answered: Does HM really help enhance SA? Do pilots recognize problems more quickly? Do they recover more accurately? Might HM aggravate complacency problems?
- Plan would call for testing with next generation commercial or military Flight Management Systems.

### **Partitioned Monitoring**

- Customer specific configurable partition for tailoring SOP or compliance gate monitoring.

### **Specialized Monitoring**

- High-level assessment, monitoring and alerting based on the integration of multi-sensor data.
- Predictive capability – "don't tell me the flaps have been over-spiced, tell me if and when an over-speed condition is likely to occur. Safe until late is OK, but if you can provide time-horizon prediction – do so."

### **Pilot Training**

- Implement a version of the Intelligent Tutoring System prototype which can be used to check pilots against a representative hazard set, or infrequently encountered checklists.
- Aiding component could drive multi-media training / tutorial system.
- Reduce student and instructor pilot time; maximize effectiveness of simulator time; provide for rich post-flight review of performance.

### **Post-flight analyses**

- Data reduction – HM used to reduce QAR data sets from commercial fleet for detailed analysis. Flexible exceedences specification.
- Trending (FOQA) – Implement customer requirements to collect and trend QA information.

### Automatic Dependent Surveillance-Broadcast (ADS-B)

- FANS / Conflict Probe - Route conformity / altitude discipline, ATC up-link consistency checking.
- Violations and restrictions checks would need prediction capability.

### Information Management

- Display highlighting and reconfiguration.
- Flexible selection of notification modality – monaural audio, text, speech, 3-D stereo, synoptic displays, animated displays.

### Adaptive Aiding

- Authorized system state changes / commands by consent.

### Summary

#### Unique Hazard Monitor features:

- Pilot-centered, context-sensitive monitoring
- Procedure de-confliction
- Sensor disagreement aiding
- Focus on hazard-prone descent and approach phases
- Preparatory guidance
- Debriefing support
- Performance evaluation

#### Aiding prototype ready for evaluation!

- Easily integrated into simulations and actual avionics
- Portable demonstration and testing environment

#### Training prototype ready for implementation!

- Draw upon pre-existing functionality, commercial software, and knowledge base development tools and processes

### List of Acronyms

ACAWS	Advisory, Caution, and Warning System	MRO	Maintenance Repair or Overhead
ADS-B	Automatic Dependent Surveillance Broadcast	NASA	National Aeronautics and Space Administration
ATC	Air Traffic Control	NAV	Navigation
CAWS	Caution, Advisory and Warning System	PA	Pilots Associate
CFIT	Controlled Flight Into Terrain	POS	Position
CRM	Crew Resource Management	PVI	Pilot Vehicle Interface
DARPA	Defense Advanced Research Projects Agency	QA	Quality Assurance
EICAS	Engine-Indicating and Crew-Alerting System	QAR	Quick Access Recorder
FANS	Future Air Navigation Systems	SA	Situation Awareness
FMS	Flight Management Systems	SBIR	Small Business Innovation Research</TD

FOQA	Flight Operations Quality Assurance	SOP	Standard Operating Procedure
GPWS	Ground Proximity Warning System	TCAS	Traffic-alert and Collision-avoidance System
HM	Hazard Monitor	USAF	United States Air Force
INIT	Initialize	V <sub>MIN</sub>	Minimum Safe Airspeed
KB	Knowledge Base	V <sub>MO</sub>	Maximum Safe Operational Airspeed
MCP	Mode Control Panel	VVI	Vertical Velocity Indication

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# **Design for a Knowledge-Based Decision Support System to Assist Near Littoral Airborne Early Warning (AEW) Operations**

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## **Abstract:**

This paper describes the design and early development of a demonstrator Knowledge-based Decision Support System (DSS) to support near littoral helicopter based Airborne Early Warning (AEW) operations. The scope of the application is large, encompassing: Detection, Situation Assessment, Reporting, Tactical decisions, Fighter control, Radar/sensor handling and Airmanship.

The design has focused on the requirement to provide extensive modularity to support extensibility and component reuse (both of the underlying expert knowledge and the associated implemented modules). The modules have been identified as the core functionality required to perform the tasks involved in an integrated manner. A multi-agent approach has been chosen which follows the guidelines laid out in the Common KADS agent and communication models, and which uses as its implementation language the D-Muse distributed real-time AI toolkit. D-Muse provides: object, blackboard, rule-based and distributed programming, to support modular development; and run-time process management providing capability for dynamic reconfiguration, which supports the efficient use of resources and error recovery.

The paper describes how the many functional components of the proposed DSS

are supported within the proposed agent framework, and how the implementation will be realised using the features of the D-Muse toolkit. The paper also touches briefly on how the complexity of the task and the work involved was estimated from the knowledge gained from close liaison with AEW operators.

## **Keywords:**

AEW, Real time, Knowledge based, Decision Support System, agent, knowledge acquisition, REKAP, D-Muse, PCPACK, KQML, KADS.

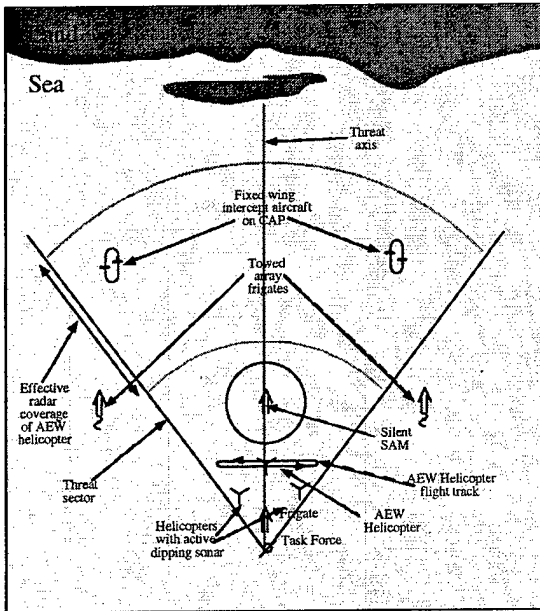
## **1 OVERVIEW AND OBJECTIVES**

### **1.1 Overview of the AEW Task**

Figure 1 shows a snapshot of a typical AEW scenario, in which AEW helicopters are responsible for protecting an advancing naval task force.

The primary elements of the scenario include:

- a) the task force being protected;
- b) a frigate forward of the main force hosting the AEW aircraft;
- c) a further frigate well advanced of the



**Figure 1: Typical Naval AEW Scenario**

task force used as a weapons platform against incoming threats;

- d) an AEW helicopter ahead of the task force searching for contacts and controlling the AEW operation;
- e) fixed wing intercept aircraft well ahead of the force, in combat air patrols (CAPs) defined by the AEW helicopter, awaiting intercept request from the AEW helicopter;
- f) further frigates on the task force flank used for ASW towed array operations (passive sonar); and
- g) further helicopters ahead of the task force performing active sonar dipping in ASW operations.

It is the task of the AEW helicopter to classify as early as possible all hostile airborne contacts in the vicinity of the task force, and to initiate the prosecution of those contacts it believes represents a threat to the task force, by efficient management of available assets.

## 1.2 Objectives of the Demonstrator

The purpose of this Decision Support System (DSS) is to develop a system which can be used to assess the expected increase in operational effectiveness of the Future Organic Airborne Early Warning (FOAEW) platform when operators are supported in their task by intelligent decision aids. From a successful demonstration of capability and improved effectiveness of operators, is the potential of moving the application toward a full mission system.

It is important to note that the proposed decision aid is not intended as an autonomous system with which the FOAEW operator has minimal interaction. Instead, it is required to be a co-operative system in which the system and operator are able to utilise the skills most appropriate to their capabilities. Even if it were technically feasible to provide an autonomous system, it is not obvious that this would be a desirable feature, since such a system would risk leaving AEW operators with no obvious control or responsibility over the progress of the sortie.

## 2 FOAEW DSS SCOPING

The bases of the application scoping was the results obtained from many Knowledge Acquisition (KA) sessions. Each session focused on eliciting knowledge from an AEW expert with many years experience, and with knowledge of the likely evolution of present day AEW towards FOAEW. During this phase a semi-structured interview technique was employed in order to provide the necessary wide breadth of coverage of knowledge required for the scoping exercise. All sessions were recorded and transcribed (using the KA toolkit PCPACK, described later) providing a permanent record of the interviews, which

will be available for reference throughout the development of the DSS [1].

The main roles for maritime forces in FOAEW were identified as Surveillance, Attack Co-ordination, Airmanship (including self-defence and safety) and Communications. Tasks in support of these capabilities include radar and sensor handling, detection, situation assessment, tactical decision making, fighter control, reporting and airmanship. For each of these tasks different levels of support were identified, ranging from routine activities to those requiring active intelligent processing. Eleven possible areas of support for the FOAEW tasks were identified (see figure 2). These provide the sub-division of the major functions likely to be involved in performing FOAEW. For each of these areas, specific tasks were identified in which a DSS could provide operator support.

Area	Tasks
<b>Barrier Positioning</b>	Advice on optimal barrier position and orientation. Advice on optimal barrier height.
<b>CAP Control</b>	Advice on optimal CAP position. Advice on optimal CAP height. Advice on optimal CAP orientation. CAP management (e.g. re-fuelling, order of replacements).
<b>Radar-Sensor Handling</b>	Advice on optimal radar scan direction, power, modes and switches. Advice on anti-jamming strategies. Advice on ESM management. Advice on IR scan direction.
<b>Tactical Decision Making</b>	Advice on optimal search sectors. Automatic prioritisation of in-bounds via the threat posed. Generation and monitoring of expected behaviour patterns and tracks (e.g. predicting intercepts well in advance by automatic generation of expected kill lines and weapon release lines).

	Monitoring of position relative to safe lanes (for assessment of when and in which direction to return to force).
<b>Prosecution and Attack Co-ordination</b>	Automatic transfer of attack orders. Calculation of predicted intercept positions. At intercept, display direction where CAP going next.
<b>Reporting and Datalink Management</b>	Aid in the efficient use of datalink resources available to FOAEW (i.e. overcoming bandwidth limitation) for transmitting high-quality information. The intelligent filtering of incoming data
<b>Database Management</b>	Search and pattern matching of mission information (Air Tasking Order, OPGEN, OPTASK). Search and pattern matching of emitter information (ESM data library). Search and pattern matching of intelligence information.
<b>Airmanship</b>	Monitoring of fuel. Monitoring of position relative to mother ship. Monitoring of changes in weather. Monitoring of fighter and weapon states. The alerting of operators to possible safety hazards.
<b>Self-defence and Safety</b>	Display of appropriate positions of mission engagement zones (MEZs) around surface contacts. Monitoring of position relative to surface MEZs. The alerting of operators to possible MEZ encroachments.
<b>Secondary Roles</b>	Route planning for probe, attack support and OTHT (i.e. ASuW). Advice on search and rescue (SAR).

Figure 2: Areas of Intelligent Support

### 3 DESIGN METHODOLOGY AND KA TOOLS

Although the initial scoping phase utilised semi-formal interview techniques, the

current design phase is employing a more formal approach using a proven methodology, REKAP (REal-time Knowledge Acquisition Procedure), and a knowledge acquisition (KA) toolkit, PCPACK, which is a practical realisation of the methodology.

### 3.1 REKAP (Real-time Knowledge Acquisition Procedure) Method

REKAP is a set of guidelines for structuring knowledge acquisition. REKAP makes the development of knowledge-based systems more efficient by helping reduce contact time required with experts. It allows a rapid transition from the description of the FOAEW 'knowledge model' to the implementation of the DSS in an appropriate AI programming environment.

REKAP uses the KADS [2] four-layer model of expertise as its framework for integrating the knowledge acquisition techniques with more conventional techniques of real-time structured analysis. The four KADS layers are:

- the *Domain Layer* describing the structure of objects in the application: for example, the typical speeds of different aircraft;
- the *Inference Layer* outlines the basic problem-solving steps and reactions to events: for example, the use of new sensor data to confirm the identity of an aircraft;
- the *Task Layer* describes the composition of tasks and system processes: for example, the breakdown of actions involved in the generation of route plans; and
- the *Strategy Layer* indicates task priorities and the interactions between processes: for example, monitoring helicopter status while identifying aircraft and planning routes.

REKAP provides the knowledge engineer, and application developer, with:

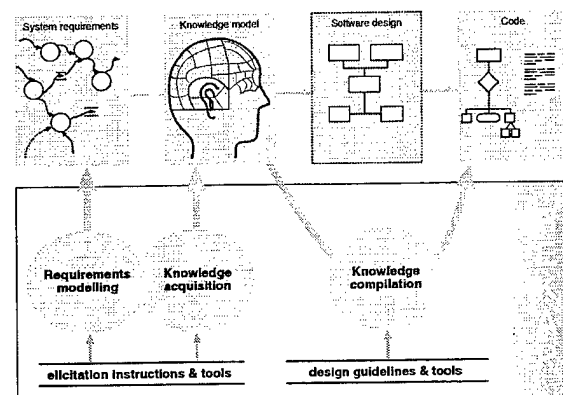
- a structured method for building real-time knowledge-based systems efficiently, using knowledge acquisition (KA) and traditional system engineering (SE) techniques;
- a unified framework for requirements definition, knowledge acquisition and application design;
- a set of instructions for using knowledge acquisition techniques and tools to elicit and structure information; and
- a set of instructions for translating a knowledge model into an application program.

This relationship between KA techniques, knowledge concepts and implementation structures is shown in the table of figure 3.

Level	SE & KA techniques	REKAP Concepts (Framework)	MUSE Constructs (Target)
DOMAIN	Laddering Card Sort RepGrid, Induction Data Structure Definition Inference Element Generator	Object, Attribute Value, Relation  State, Event, Action	Schema, Instance Relation  Rule clause
INFERENCE	Card Sort RepGrid, Induction, Matrix Tool Process Specification Control Specification	Inference Complex Primitive Task	Rule I/O Handler, Demon Procedure Method
TASK	Laddering Data Flow Process Decomposition	Task Hierarchy	Ruleset, Noticeboard Knowledge Source Agent
STRATEGY	Laddering, Card Sort Control Flow	Task Priority Task Interaction Task Interruptibility	Event Priorities Interrupt Structure Inter-agent Control

Figure 3: REKAP Framework.

The process of applying the methodology to a particular domain is shown in figure 4.



### **Figure 4: Use of REKAP**

The information derived, through the application of these methods and techniques, includes:

- design documents, including annotated data flow diagrams, generated as a result of applying the methodology during KA sessions with domain experts, and
- skeletal code definitions, including object class definitions and the identification of program modules, from the translation of the tool data, generated from the KA sessions.

### **3.2 The Generalised Directive Model (GDM)**

An important part of the design process using REKAP is the identification of the GDMs (Generalised Directive Models), for the tasks of the application.

The GDM comprises a statement of the inference steps performed during problem solving (for example, abstract, match and refine), the classes of domain descriptions serving different problem solving roles (PSR) within the model (for example observables, variables, abstract solutions and specific solutions) together with the dependencies between the two.

These inference steps and roles correspond to partitions in the knowledge of the system. Aiding acquisition and the organisation or indexing of the knowledge required for the system to function.

For example, a directive model for performing situation assessment could be to match the known features of a particular contact (track) with typical descriptions of certain types of objects (schemata).

### **3.3 KA Toolkit: PCPACK**

Although not essential to the design process, significant benefits accrue from using an appropriate toolkit in support of KA. For the FOAEW DSS knowledge acquisition is being supported by the KA toolkit PCPACK [3]. PCPACK consists of an extensive collection of KA tools, KADS style directive models, and facilities for supporting project management and documentation. These include:

- GDM Workbench;
- Protocol Editor (or Transcript Analysis tool);
- Hyperpic tool;
- Laddering tool;
- Matrix tool;
- Card Sort tool;
- Repertory Grid tool;
- Case Editor and Rule Induction tool;
- Rule Editor;
- Project Management; and
- Project Documentation.

The KA toolkit binds the various tools together using an object database, within which the instances of concepts derived by each tool, and their inter-relationships, are stored. The integrated database allows the different facets of the stored knowledge to be viewed and manipulated by other tools in the toolkit.

### **3.4 Estimating Complexity**

The methodology provides developers with the necessary metrics in which the complexity of the application can be assessed from the design, and thereby building confidence in the development process.

A earlier decision support system for Anti-surface Warfare (ASuW) provides

supporting evidence for this claim. This application was developed according to the same methodology, but utilised an earlier KA toolkit (PROTOKEW) together with a translation tool (PKTOMUSE) capable of translating the knowledge model directly into the structures of language used in its implementation (according to the mapping described in the table of figure 4, above). In the *situation assessment* task for this system virtually all of the schemas (class definitions) were provided by the application of the translation tool to the knowledge model, while the task decomposition was able to identify and detail each of the system's inference stages.

However, the accuracy of estimating the size and complexity of a task is very much dependent on nature of the task.

For example, past experience has demonstrated that problems involving certain types geometric reasoning are more difficult to assess, because the methods employed by the human operator cannot be easily captured in a way that can be implemented on a computer (e.g. the assessment of the quality of flight plans appears to be easy for an experience operator to perform, but is extremely difficult for a computer based solution).

Since a similar design approach is being used for the FOAEW DSS, it is expected that similar outputs will be available from the process.

#### 4 DETAILED KA FOR FOAEW

All of the KA carried out during the detailed design phase for the FOAEW DSS is being captured using the PCPACK toolkit, which will be used to provide a knowledge model for each of the tasks identified during the scoping phase.

An example, taken from one of the FOAEW tasks nearing completion is *Barrier Positioning*. Figures 5 and 6 show the first level description for this task, and the decomposition of one of its sub-tasks.

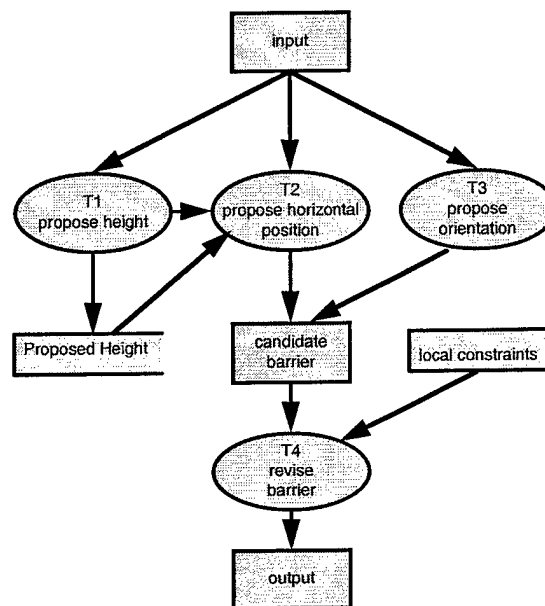


Figure 5: Barrier Positioning Control

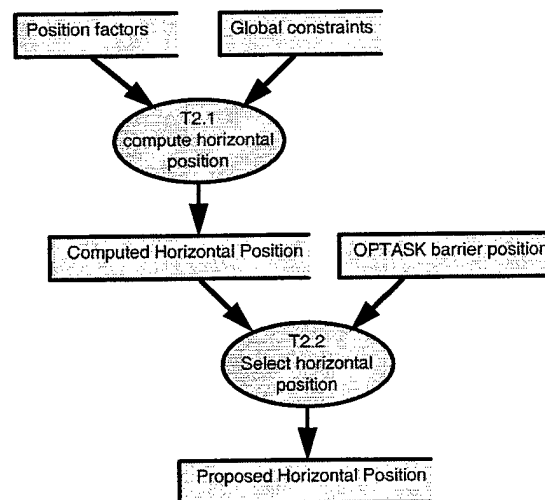
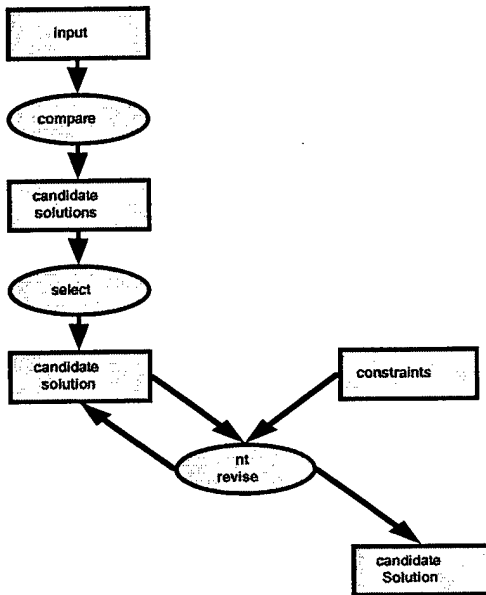


Figure 6: Decomposition of Propose Horizontal Position

Abstracting out the decomposition provides us with an appropriate GDM for the task,

which is identified as an instance of a *compare-select-revise* model (figure 7).



**Figure 7: GDM Identified for Barrier Positioning**

The design process is often found to be iterative, since the GDM may be unknown until an initial examination of the task has been carried out. Subsequently, an appropriate GDM may be identified but it is found that it does not completely match the task decomposition. In this case it may be desirable to reassess the task to see if it can be recast to match the GDM more closely.

## 5 IMPLEMENTATION TOOLKIT: D-MUSE

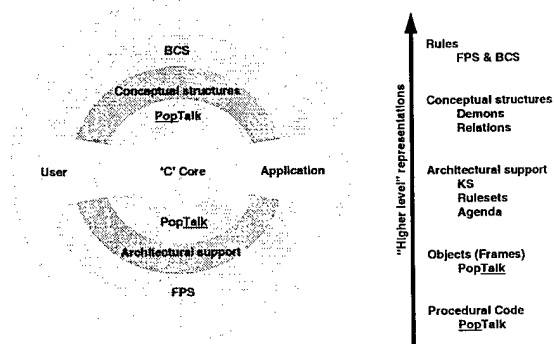
The proposed implementation framework for the FOAEW DSS is D-Muse [4], a real-time knowledge based toolkit for the development of distributed applications.

D-Muse provides facilities for running a collection of named processes, that are inter-connected by a network of deadlock free communication paths. Each Muse process provides the following functionality, appropriate to the structures required by the

REKAP method:

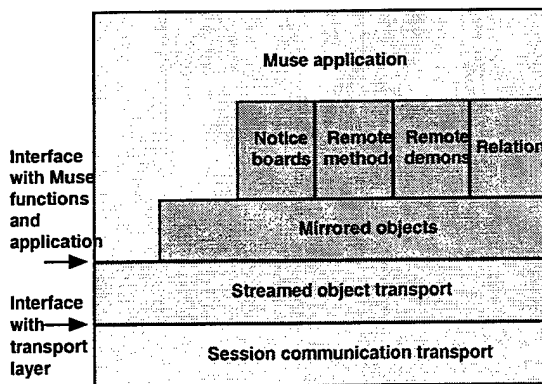
- *flexible knowledge representation*: including forward chaining production rules, backward chaining rules and frames;
- *support for modular code development*: by segmenting domain code into separate knowledge sources and shared databases, such as blackboard, rule sets and notice boards;
- *support for real-time operation*: including agenda-based priority scheduling, interrupt handling and data capture, and the D-Muse communication facilities; and
- *extensible*: many features of D-Muse can be customised using the built-in object-orientated language (PopTalk) or through a 'C' level interface allowing specialised reasoning structures or access to any external software accessible from 'C'.
- *distributed object management*: provides the mechanism to share information between Muse processes in real-time while ensuring consistency (streamed and mirrored objects).
- *session management* allows the creation and deletion of D-Muse processes at run-time.

The core knowledge-based features of a Muse process are depicted in the following diagram, figure 8.



**Figure 8: D-Muse Process Architecture**

While the D-Muse extensions are represented in figure 9.



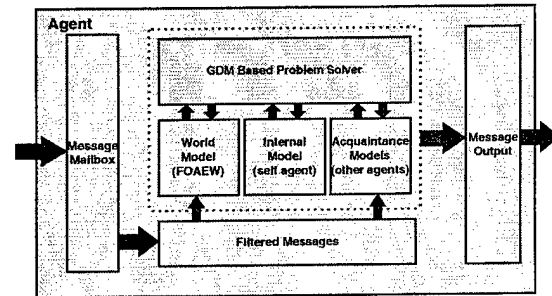
**Figure 9: D-Muse Process Architecture**

D-Muse is not restricted to inter-connecting Muse processes, but can also be used to communicate with other processes, such as graphical user interfaces and simulation facilities.

## 6 ARCHITECTURAL DESIGN

Another important goal for the FOAEW DSS is that it should provide an extensible implementation that supports, where possible, the reuse of components, and the ability to grow the system without having to re-engineer components. To achieve this, an agent based architecture has been chosen, which is being implemented within D-Muse.

The internal architecture for the agent is being designed so that they can be populated directly from the knowledge models created during the design phase. Figure 10 shows the proposed agent structure.



**Figure 10: Agent Architecture**

Excluding the modules responsible for the input and output of messages, the agent has four distinct components:

- GDM based problem solver, which implements the main task of the agent (e.g. route planning, situation assessment and barrier positioning).
- World Model, which provides the agent with its current understanding of the world (in our case the FOAEW sortie) (including general principles, state descriptions, predictions and facts).
- Internal Model, this defines the agents understanding of its own behaviour (including beliefs, principles, objectives, goals, intentions, plans, capabilities and language/ontology).
- Acquaintance Models, representing the agents understanding of other agents it knows about (including objectives, capabilities and language/ontology).

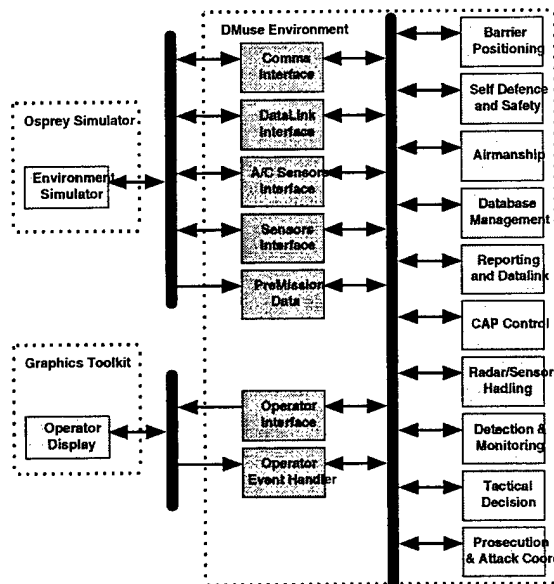
Analysis of the task decomposition and its GDM will identify the requirements and capabilities of the agent. In particular, elements of the world model will be defined by the input and output parameters to the GDM. Requirements and capabilities will be broadcast (handled by a *facilitator* agent) to the other agents of the system. The other agents are able to respond with offers of appropriate information, or with requests to utilise the capabilities offered by the agent.

For example, the identification of MEZs, important for safe route planning, can come



from many different sources, some of which may not be implemented in the initial DSS. The addition of further agents that expand the scope of MEZ identification is facilitated by the autonomy offered in an agent architecture.

The following diagram, figure 11, shows our initial application architecture.



**Figure 11: Key Software Components**

The agents on the right represent the kernel functionality of the system, the central set of agents define the support agents that interface with, in our DSS, a simulator and a workstation based operator interface. This decomposition is not definitive. Changes are already being considered to partition a number of the agents into smaller agents, with more specific responsibilities, which then report to a controlling managing agents.

## 6.1 Agent Communication Language

The agent communication language chosen for the FOAEW DSS is the Knowledge Query and Manipulation Language (KQML). KQML [5] is a language independent message format and message-handling protocol designed to support run-

time knowledge sharing among agents.

The KQML language defines a set of messages, or "performatives", that can be used for communication of a broad collection of broadcasts, queries and replies between agents. These performatives provide agents with an ability to:

- advertise their capabilities,
- request information from specific or unknown agents,
- dispatch information in response to other agents' requests, and
- request agents to modify their world model.

Due to the language independence of KQML, the actual content of messages is opaque to the KQML layer (unless the content is itself KQML), and requires the message to be supplemented with attributes defining the language it is expressed in: Prolog, Lisp, PopTalk, etc., as well as the ontology (i.e. context) it assumes.

However, for Muse implemented agents (this will apply to most of the agents within the DSS), only the semantics of KQML will be implemented. The syntactic sugar surrounding the message will be removed and the messages communicated between agents as Muse objects. Where agents are on different processors, requiring inter-processor communication, D-Muse streamed objects will be used. This approach, acceptable within a Muse based homogeneous implementation, significantly improves the efficiency of the system, because there is no need to generate and parse the KQML syntax.

However, where there is a need to communicate with agents that have not implemented in the Muse language, or do not support D-Muse streamed object communication, the full syntactic form of

KQML messages will be employed.

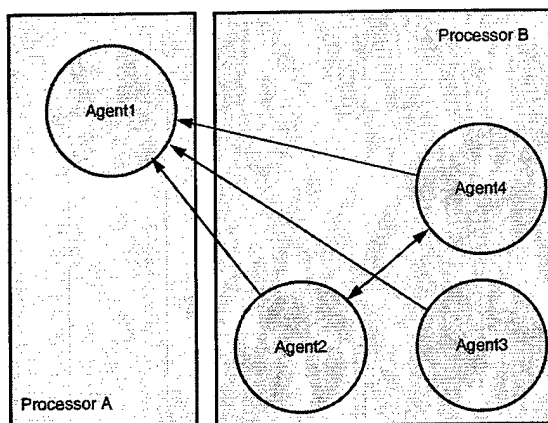
To make the messaging transparent, the system will use the *acquaintance models* built up by the agents of the system to provide an agent with the language and ontology required by the agent receiving the communication.

This approach will aid future desires to integrate the DSS with legacy systems, such as intelligence and emitter databases.

## 6.2 Optimisation of Inter-agent Communication

An agent defines a logical partition of functionality within the application, but does not require that it be localised to a single processor. A proposal is currently being investigated of ways of distributing agent functionality across processor boundaries to find ways of improving efficiency of inter-agent communication in a distributed environment.

For example, consider the following, figure 12, where *agents* 2, 3, and 4 all regularly request information from *agent* 1.



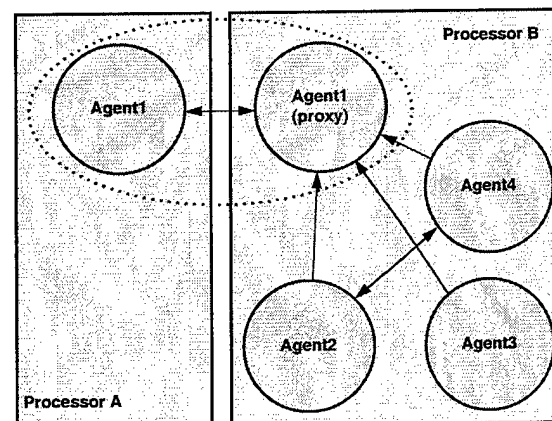
**Figure 12: Inter-agent communication without optimisation**

If each agents requires the same information (i.e. results of situation assessment applied to an ingressing aircraft), separate inter-

processor messages require to be generated for each agent.

The proposal is to define a "proxy" for the agent which can reside on the same processor as the agents requesting the information. All messages to *agent* 1 are first directed to the proxy, which will attempt to satisfy the request locally. If the request cannot be satisfied locally the message is redirected to processor containing the agent proper. This is depicted in figure 13.

In terms of its implementation it is envisaged that this will involve sharing elements of the world and acquaintance models across processor boundaries (implemented using D-Muse mirrored objects).



**Figure 13: Inter-agent communication with optimisation**

## 6.3 Fault Tolerance and Agent Mobility

Since the proposed D-Muse agents can be created dynamically across any of the available CPUs, the run-time system provides capability for implementing a limited degree of fault tolerance within the DSS. For example, if a processor dies it is possible to terminate the function of low

priority tasks, and use the freed resources to host new instances of agents from the lost processor.

Although it is technically feasible, there are many issues relating to acceptable grade of service and system consistency to be addressed.

D-Muse agents also provide the ability to support mobile agents, which can be moved (intact) at run-time. However, a need for such capability within the FOAEW DSS as yet to be identified.

## **7 CURRENT STATUS OF THE FOAEW DSS**

At present, the project is entering the final stages of its design phase, with knowledge elicitation for a number of tasks still ongoing. As such the information presented here is still subject to change. However, it is intended that the philosophy of the design, should be retained.

An experimental general agent framework has been built and is being used to refine the ideas for a practical agent structure for the application, which will be optimised for the application. Ways of importing the tasks, via their GDM, into the agent architecture, and addressing issues of maintenance of the world model are also being addressed.

Although a translation tool exists for the earlier KA tool (PROTOKEW) to Muse, the present toolkit does not yet have this facility. However, Epistemics are investigating the possibility of providing such a tool, and it is hoped that by the time implementation of the DSS begins this shortcoming will have been addressed.

## **8 CONCLUSION**

The methodology, design tools and the

proposed agent architecture for the FOAEW DSS provides the developers with confidence in the development of the application.

In particular, the close relationship between the methodology, its realisation in the PCPACK toolkit and the ability to map the knowledge concepts directly onto features of the implementation language, provide a means of estimating the size of the application (including the size and quantity of data structures, and the complexity of the various functional areas and tasks of the application).

The utilisation of an agent architecture, although grounded more in practical implementation rather than a theoretical implementation, provides the developers with means of reusing software components and supporting future modular expansion.

The use of KQML style communication between agents of the application, allowing easily transition into the KQML syntax for communication with external data sources that will grow in importance as the system expands.

## **9 ACKNOWLEDGEMENTS**

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- Lt. Cdr. M. Roper, RN (AEW Desk Officer, DOR(Sea) RNA7)

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# COPILOTE ELECTRONIQUE PROJECT

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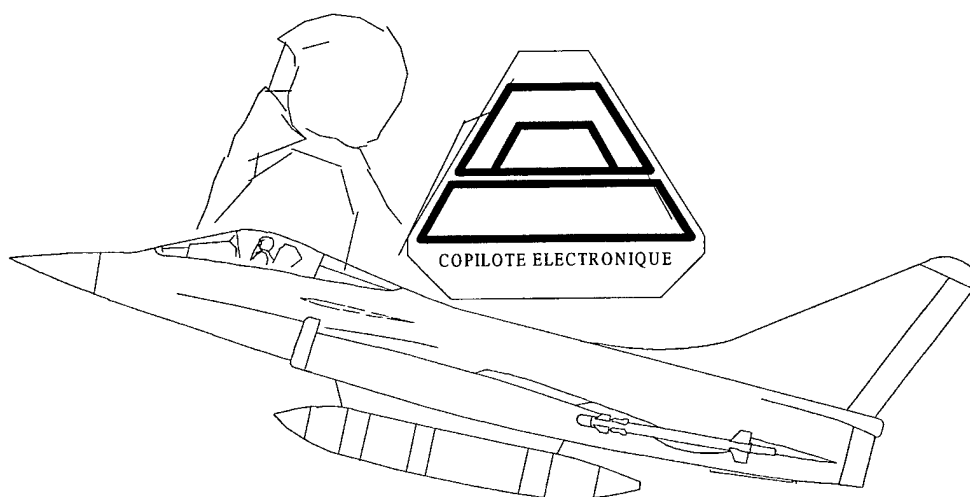
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## I. INTRODUCTION

Since 1994, the Technical Service for Aeronautical Telecommunication and Equipment of French DGA (DCAE/STTE then DSA/SPAE) launched an exploratory development program concerning a high level decision aid, using Knowledge Based System (KBS) technology for an advanced combat Aircraft. This french project for an in flight mission replanning Decision Aid is called "Copilote Electronique" [Champigneux 1989].

The exploratory development program is led by Dassault Aviation with the support of many industrial and scientific partners (SAGEM, Dassault Electronique, Matra BAe Dynamics, Sextant Avionique, IMASSA, ONERA...).

It aims at introducing this kind of decision aid within a 2010 horizon for a future Rafale standard (The Rafale aircraft will enter the French Air Forces at the start of the next century).



## I. OPERATIONAL OBJECTIVES

- The operational objectives of the Copilote Electronique are surveyed in order to precise the domains of assistance that are relevant for such a system.

Before the launch of the Exploratory Development an action was initiated by DRET the french military research agency to survey the need for pilot assistance in french airforce programs and the feasibility of KBS as a potential technical answer (DRET 86.34407 faisabilité d'un Copilote Electronique and DRET 89.34565 Méthodes permettant le développement d'un Copilote Electronique). The need was expressed by senior pilots of the french airforce and navy, with experience of Mirage F1, Mirage 2000 and Super Etendard. The cognitive analysis of pilots activities was conducted by CERMA (Centre for Medical studies and research in Aerospace).

Within the context of the Copilote Electronique program this initial survey was completed and reviewed in front of the forecasted definition of the Rafale missions and system standards. This involved a specialist of the Rafale program from the CEAM (French air force test center) as well as Dassault test pilots currently involved in the definition of the new program.

This section do not address specific requirements linked with the Rafale program but the generic needs of an onboarded mission planning activity in a future combat aircraft.

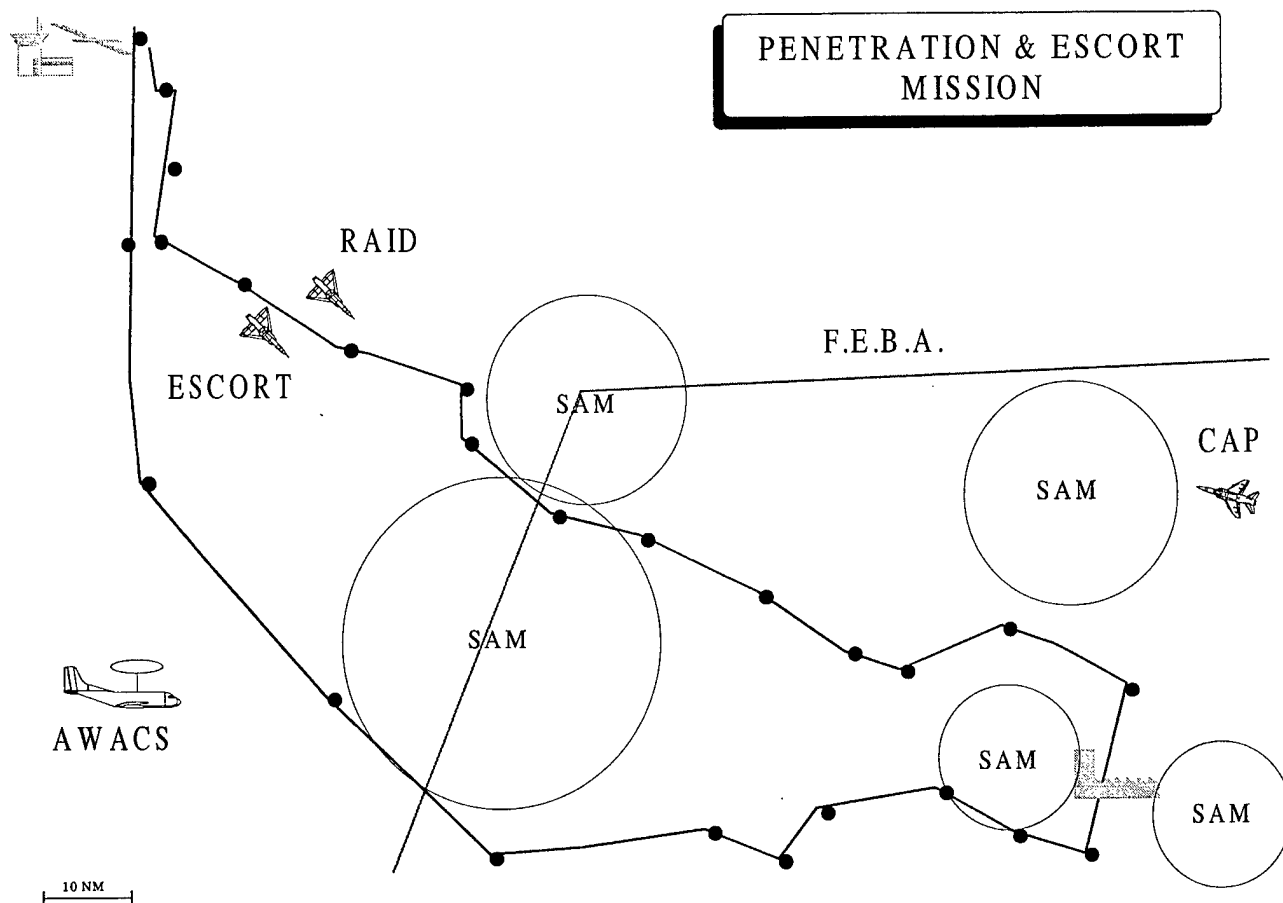
Conducting penetration missions in hostile territory has always raised problems of workload on single pilot. Regardless of aircraft configuration and avionics the planning activity is a very difficult task for the pilot in flight. This includes route selection, ECM employment

(like activating and shutting down jammers, throwing decoys...), flight monitoring (following profile, respecting timing, handling communication with C3I...), attack planning and weapon selection... This overload problem has generally been solved by applying strict mission control rules over a very detailed ground based mission preparation.

It is recognised for example that in a typical Penetration Mission at low altitude and high speed within enemy territory, a pilot is following a strict time schedule with little possibilities to divert from it. For instance at an altitude of 300 to 500 feet and a speed of 500 knots only a few seconds of delay over the way points can be accepted. If such timing is not followed coordination between friendly ressources is in danger, the efficiency of weapon delivery is lowered and possibly, the firing of the aircraft by friendly ground defense will happen when crossing back the Front Edge of Battle Area (FEBA).

The extreme time pressure imposed on pilots of combat aircraft makes the planning activity very complex and dynamic. With such an extreme time pressure, in-flight planning could be considered as totally unrealistic, but it must be recognized that most of the time real missions will be disturbed by unexpected events. This leaves no choice to the pilot who needs replanning.

We have listed many of those unexpected events in the domain of aircraft ressources. One may mention engine failures, jammed positioning systems, sensor default... They are also numerous and frequent in the tactical domain. For instance one will encounter hostile Counter Air Patrol aircrafts (CAP), unknown ground missile sites (SAM), electronic counter measures... There are of course perturbations due to the natural mission conditions such as weather evolutions, unregistered ground obstacles... Finally one have to mention coordination problems between raid and escort patrol or Command and Control aircraft (AWACS) as well as possible human errors.



Therefore a strictly nominal execution of a mission plan prepared on ground is very unlikely to happen according to our experience of Mirage F1 CR or Mirage 2000 operations as well as Rafale extrapolations. Even simulation campaigns will show frequent perturbations with the necessity for the pilot to react by in flight mission planning. A recent Rafale simulated test of a sweep mission exemplified the interest of some pilot support in heavy workload situation.

In such cases the functional requirements of pilot planning task ranges from flying activities, navigation, ressources management, information pick up, to tactical response elaboration.

For instance we analysed in detail an Air to Air Engagement during an escort mission. In case of ennemy engagement, a pilot has to planify an adapted behavior to analyse the tactical situation including platform manoeuver and sensor control. He needs to coordinate the friendly actions through communication with the penetrating raid bomber leader and with its fighter wingman. He exchanges tactical information,

selects tactics, assigns target and he instantiates a proper offensive plan including weapon preparation, launch point calculations, flight path trajectories generation, evaluation of kill and survival predictions...

In conclusion of this section we can assess that a requirement for in flight mission planning is perceived in future low altitude high speed penetration missions and air to air escort missions (this is not to say that in flight planning is not needed on other missions such as air to air interception at high altitude but this analysis was not carried exhaustively within the scope of our project).

The planning task not only concerns navigation strategies but also tactical offensive and defensive management as well as aircraft ressources monitoring. These many planning concerns overlaps during active mission phases such as air to air engagement. Consequences of bad planification as taking wrong decisions, acting too late, or executing improperly the plan, are generally intolerable. It may result in a crash,

or an unsuccessful mission, or the loss of aircraft and pilot ...

A single pilot with current avionics is unlikely to perform such in flight planning complex task without errors. A need for assistance is perceived, leading to increased automation as well as planning support. We noticed during our analysis phase of the Copilote Electronique that there is a general preference for systems providing assistance in tasks such as calculating fuel, plotting routes, identifying risks... Pilots really care for better situation assessment in the planning process. This was well expressed by Major G.W. Breeschoten in his keynote address of Guidance and Control Panel 53rd Symposium [Breeschoten 1992]\_:

"I do not want the system to think for me, at least in the sense that it prescribes my tactical actions. It can to some extent think with me."

Nevertheless, as critical decisions are to be taken on uncertain or tactical aspects of mission, aircraft designers often rely on pilots judgement. This tendency is even currently required by Air Forces.

As a result of this requirement analysis the Copilote Electronique project is oriented toward a multi-agent (or multi-assistance) organisation that best express the human reasoning in the guidance and control domain. For the development phase of the program it was then decided to consider the expert domains that pilots distinguish in the conduct of penetration and escort mission.

These domains are:

Aircraft system management (« domaine Avion ») including:

- System Evaluation
  - . Monitoring discrete events and continuous signals.
  - . Assessing real avionic systems states and dependability.
- System planning
  - . Planning the avionic systems reconfiguration.
  - . Scheduling of action & resources according to the plan.

Tactical management (« domaine Tactique Sol » & « domaine Tactique Air ») including:

- Tactical assessment
  - . Analysis of friendly & foe forces.
  - . Elaboration of forecasted evolutions.
  - . Assessment of risk/efficiency according to present plan.

- Tactical planning
  - . Planning tactics according to the threats and pilot strategies.
  - . Scheduling actions and resources according to the tactics.
  - . Handling conflicts among proposed tactics.

Mission management (« domaine Mission ») including:

- Mission condition Assessment.
  - . Mapping of pre-mission meteorological briefing onto possible routes.
  - . Mapping of pre-mission geographical data onto possible routes.
- Route Planning
  - . Selecting re-routing options according to the updated mission context.
  - . Planning new routes.
  - . Monitoring possible routes with quality estimates.

Man Machine coordination (« domaine Coherence des assistances ») including:

- Pilot Behavior Assessment.
  - . Mapping pre-mission strategic option to in-flight planning.
  - . Inferring pilot intent from observed actions.
- Planning management
  - . Driving experts planning efforts toward a common goal in accordance with pilot strategy
  - . Insuring proposed plan quality
- Dialogue management.
  - . Presenting relevant informations to the pilot
  - . Handling pilot queries

## I. ERGONOMICAL DESIGN

- The advantages of a cognitive assistant approach over an automatic planning approach and the ergonomical rules settled by the project to facilitate in flight Pilot<->System relationship are presented showing the "Copilote Electronique" orientations in that respect.

To design the proper decision aid it is necessary to analyse the level of autonomy best adapted to the in flight planning process.

In front of the increasing complexity of avionic systems and weapon systems it is certainly desirable to design systems capable of taking responsibility of lots of pilot decision activities. The present technological push, best



exemplified by the well known knowledge based systems, expert systems, constraint programming tools, neural nets... leaves an open field to the dream of full automation.

Of course some caution should be taken in terms of feasibility for these techniques in real time avionics. As Wiener and Curry showed [Wiener 1980], full automation can have serious drawbacks with a risk in the long term of having operators unable to conduct the missions.

Various embedded functions, such as navigation, piloting, aircraft status management, weapons system management, and in some extension sensors management have been successfully automated by classical software engineering methods, but the addition of such separate and independent automated functions is more and more difficult to control in real time situations by human pilots.

Automated functions are intended to increase in number and complexity, in the foreseen tactical context of year 2010. Such context is characterised by a great number of various possible threats, with electronic war systems and new sophisticated weapons. Operational experts think that future pilots will have some difficulties with this combinatory explosion of information sources unless being assisted in their reasoning tasks.

Within the "Copilote Electronique" project, we cautiously analysed the tasks in terms of potential for automation and/or assistance. We based our first work on the guidelines of the AGARD advisory report on improved guidance and Control for the automation at the Man Machine Interface [AGARD 1988]. These guidelines expressed that tasks requiring highly accurate responses, fastidious and repetitive actions, and exhaustive calculations are good candidate to automation. On the other hand, tasks requiring judgement, multi-sensory information gathering, hypothetical reasoning, contingency reaction... are best suited for a "Man in the loop" design.

Planning tasks are certainly of the second type. We structured those tasks like system reconfiguration, ressources scheduling, navigation, fuel monitoring threat analysis, threat avoidance, threat engagement, Command Control and Communication, sensor control and weapon management according to the expert domains :

- System management
- Tactics management (air-air and air-ground)
- Mission management

In the System area , planning is more often an optimization of fine grain plan in front of the flight parameters evolution and generalised state of the navigation and weapon systems (including faulty states).

In the Tactics area , planning is reactive . Threats are popping up as unexpected event and disrupt from the planified behavior established on ground during the preparation phase.

In the Mission area , the result of the mission preparation remains the guide for all in flight planning. The task here consists of adaptations of the nominal plan, plan refinement in a precise context, choice of alternative plans...

At this stage of our design we have oriented our approach toward a human centered design. This was based on human factors evidences from the aviation history, which are addressed in the "Copilote Electronique" team by IMASSA/CERMA [Amalberti *et al* 1992].

This study resulted in "user oriented rules" that has to be used in the design of the Copilote Electronique.

Those rules can be summarised as follows :

- pilot anticipates and needs anticipation assistance on contrary of "classical engineer designed" assistance which are often too reactive,
- pilot's decisions reflect often compromises between mental load and ideal response to the situation, so pure optimality is not to be researched if pilot has no sufficient time to understand,
- following their own personal skills, different pilots may organise work differently, assistance must be adapted to these skills,
- assistance must be homogeneous, and it will be preferable to rely on specialised expert for each operational domain (e.g. Strike or Air Defense expertise) so resulting assistance will produce constant understanding interpretation model that will avoid surprises for pilot,
- assistance must know and respect its own limits,
- system design may use "what if" approach to be less reactive,
- dialogue must be adapted to context, pilot intents and pilot load,
- dialogue must be space oriented and interactive, better use vocal media than written, but avoid saturation,
- respect logic of pilot understanding, that means rely on the understanding model designed with expert pilots.

The french Copilote Electronique project is oriented toward a cognitive assistance as a consequence of this ergonomical analysis.

## I. ORGANIC ARCHITECTURE

- The organic architecture established for the "Copilote Electronique and the proper mechanisms supporting the cognitive assistant approach of mission planning are described.

In order to achieve the main objective of demonstrating the concept of a cognitive assistance for future combat aircraft it is necessary to organize the selected expert domains that will perform the required functionalities of in flight decision aid.

The Copilote Electronique project finalized such an architecture by the end of 1994.

The top level organization of the expert domains in the Copilote Electronique is in accordance with the Functional Decomposition of Generic decision system in Guidance and Control as proposed by AGARD Working Group 11 [AGARD 1993].

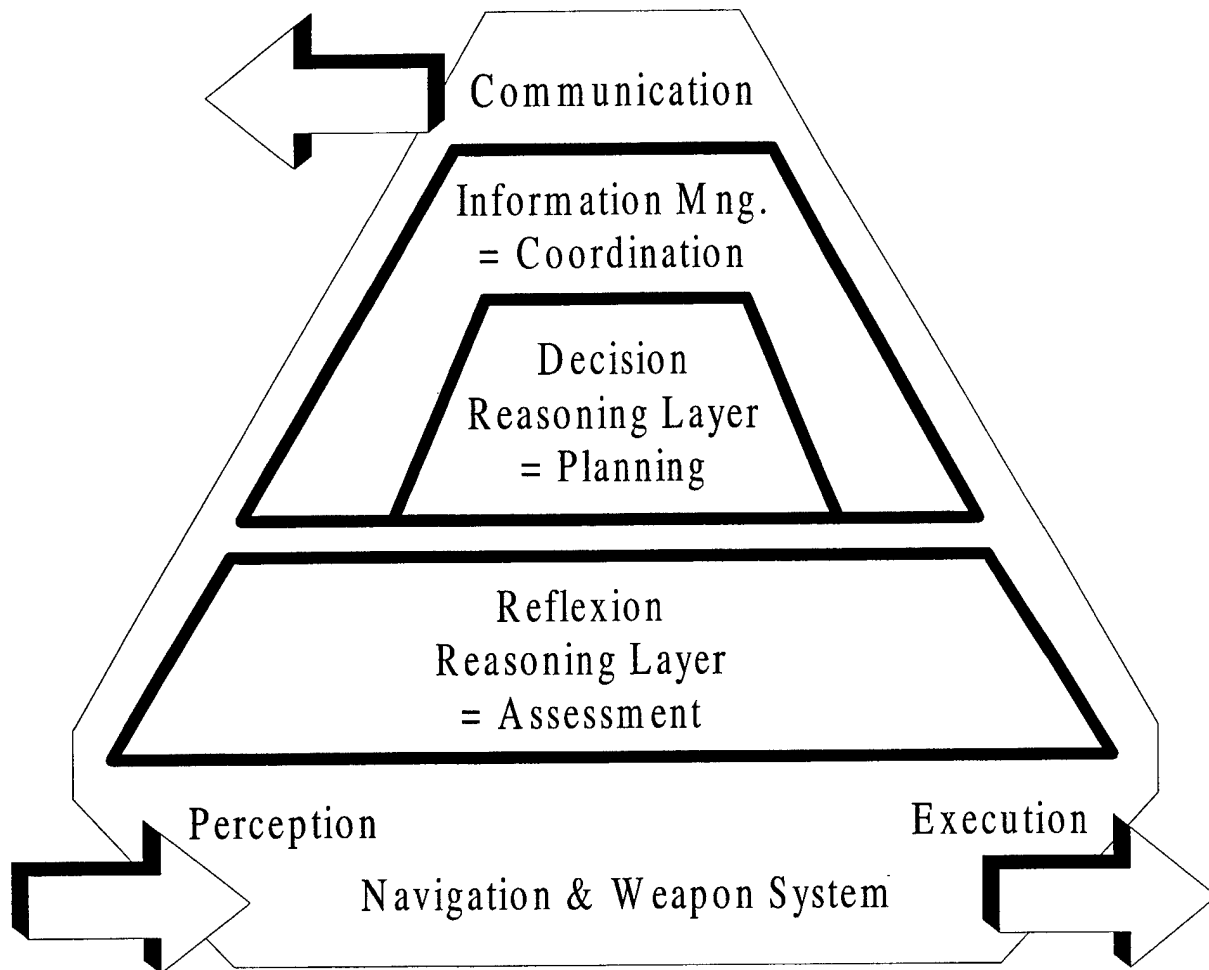
The two main activities of situation assessment and planning are represented in each of the expert domains. All the expert domains are communicating with others to enrich their vision of the situation and to elaborate plans. The coordination activity is taken in charge by a specific expert supervising the others.

An expert domain, absorbs high rates of raw information, select and highlight the more crucial ones, before initiating dialogue with the other experts. Raw data is provided by the existing technical functions of the Navigation and weapon system assuming that a data sharing mechanism is available (it is the case with Rafale and M2000 type of system).

The planning reasoning layer of each domain take entries from the assessment level. Expert description of the situation are not propagated to each domain but relevant informations can be accessed on request. Planning directives are passed by the supervising expert to the concerned specialists according to the problems encountered. Such directives includes, problem scope, constraints, and pilot strategies. The experts reason in a manner adapted to current situation and mental load of the pilot. They consider a restricted set of actions choice for the pilot and examine all consequences before proposing them.

Dialog with the Pilot is handled at the supervision expert level. It insures that a single coherent proposal will be presented by the group of expert domains. It also minimize the informational workload of the pilot and handles the pilot queries through the use of « regular » man machine interface of the Rafale aircraft.

The external world perception, the communication with other agents and the plan execution are not part of the Copilote Electronique responsibility but we can assume that these activities are present in the current Navigation and Weapon system (SNA) in which the Copilote Electronique is integrated .



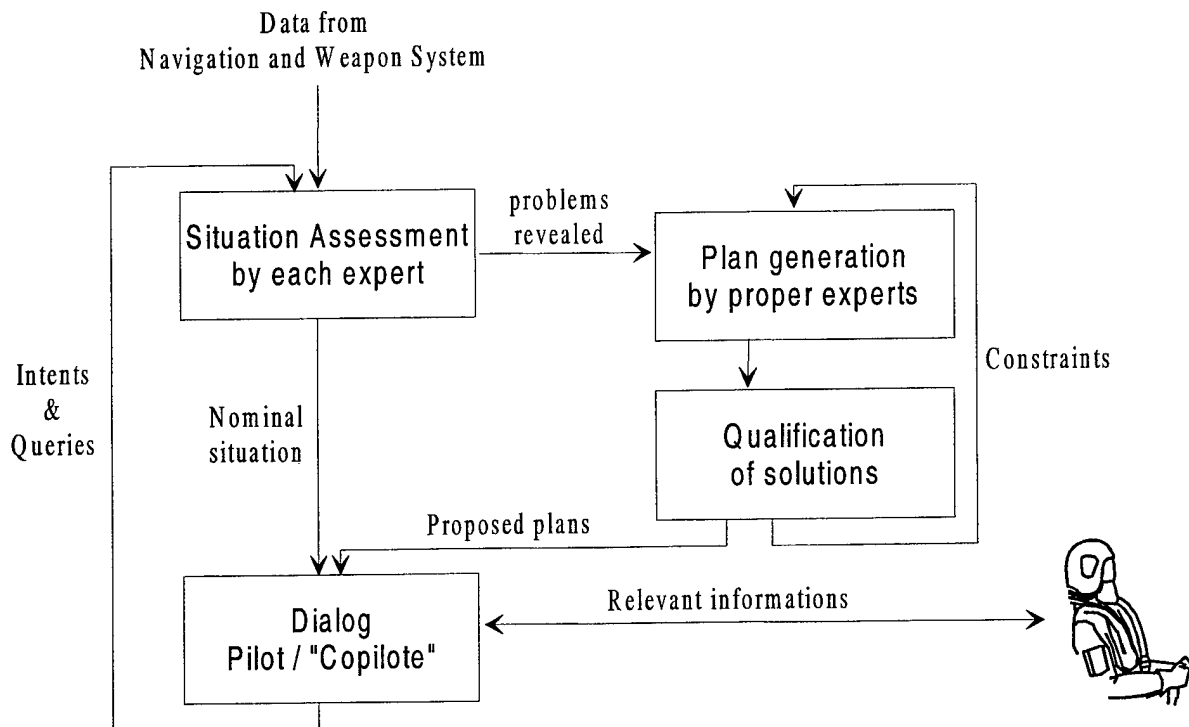
The dynamic behavior of the Copilote Electronique is driven by a cyclic assessment of the situation by the expert domains (the period of the cycle differing from one expert to another) and an event driven planning activity based on the warnings issued by the assessment layer.

The planning activity includes several steps of generation driven by the experts best suited to the revealed problem and the pilot strategy. Those steps are followed by qualification treatment. Qualification is performed by all the expert domains so that the quality of the proposed solution is seen globally and not only

by a single domain with possible conflicts with other fields. In case of insufficient quality constraints are posted by the expert domain to help the other in refining their proposal.

Once finished the planning activity gives results to the dialog manager. Plans are joined to situational information to be presented to the pilot. Two levels of dialog are handled (rich or succinct) in order to adapt the information flow to the pilot workload.

The following figure present this process:



## I. DEVELOPMENT STATUS

- A short overview of the knowledge based development process engaged is given

The goal of the functional development, launched in 1994 for a three years duration, is a ground simulation, without real time constraints, to illustrate the potential of the "Copilote Electronique" in situation of strike and escort missions, with low altitude penetration constraints.

The software architecture at this stage is resolutely a cooperative set of expert modules mapping the expert domains [Gilles 1991].

To conduct this development Dassault Aviation set up a consortium based on the french industrial competences. Responsibilities within the consortium are :

- Ergonomics rules and knowledge acquisition methods and verification tasks  
-> IMASSA/CERMA
- System Status Assessment and Management  
-> SAGEM
- Tactical Situation Assessment and Management (Ground threat and defensive Counter Measures) -> DASSAULT ELECTRONIQUE
- Tactical Situation Assessment and Management (Air threat and offensive Weapons)  
-> MATRA DEFENSE
- Mission Conditions Assessment and Mission Management  
-> SEXTANT AVIONIQUE
- Pilot Assessment, action plans assessment, relevant information management and man machine interface  
-> DASSAULT AVIATION

Knowledge engineering techniques are for expertise initial design. With IMASSA, a specific method for eliciting and formalising pilot's expert knowledge was studied and is used. It is supported by a formalisation tool called X-PERT. It is confirmed by present campaigns that pilot expertise can be collected coherently in all the expert domains and that generic

behaviors (not linked with a specific Navigation and weapon system) can be used in the expert modules. Generic expertise has to be supplemented by extensive knowledge evaluation and correction in simulator. in order to represent specific behaviors linked with the new system like Rafale. The main issue for the future design is to accept expertise from pilot during operational life of the system.

The technical specification is driven toward a flexible heterogenous implementation paradigm. The Copilote Electronique expert modules are organised in a multi-agent system using Distributed Artificial Intelligence techniques [Erceau 1991].

Another very important technical issue is the definition of a common "**plans and goals**" exchange language between all specific assistance modules, and great efforts are made to maintain this common message glossary. Within the functional development Dassault Aviation proposed an exchange language called LDI which provides a CORBA like facility for object communication.

A unifying technical principle is adopted to facilitate the architecture design via the **intent planning paradigm**. This principle is essential to fulfil general ergonomics constraints : assistance must not participate to the signalled existing overloading factors. Intent recognition is a challenging but promising direction and can be made easier by extended preparation mission plans and procedures (for each pilot activity) that will be perhaps the new "automated and personalised" check lists version of the future [Rouse 1991].

At present, a mock-up is implemented. It uses a set of unix workstations (one for each expert domain) linked to a Rafale simulator with « engineer » type of interface. The mock-up shows non real time behavior of the expert modules integrated in a complete Copilote Electronic system. A synthesis of the presented functionalities will be realised in spring 1997.

## I. CONCLUSION

This example opens to the possible future developments of intelligent decision aids for in flight tactical dynamic planning within future combat aircraft.

The technology is available today to provide viable knowledge system solutions to well-chosen and well-defined problems. It can be expected to see more and more successful projects on such on-board applications,

as both the research, the technology and engineering skills of application developers improve.

But this process may be slower than was thought. Main reason is that knowledge acquisition tasks and user oriented ergonomics rules compliance must be integrated in the overall engineering cycle.

The french Copilote Electronique project has been carefully planified considering those methodological difficulties.

After a long design phase the Copilote Electronique is now in a software development phase. The planning domains are the main drivers of this development. They are developped by french industrial partners in a federative approach. Each partner brings to the project a specific background, with a high value knowledge of his planning field and mastering of appropriate planning mecanismns. This results in a very rich but heterogeneous multi-expert, multi-industrial dynamic planning system.

The Copilote Electronique, not only reach a successful behavior in each dynamic planning field, but also achieves to demonstrate a coherent assistance for in flight decision aid. Special care is taken to analyse interdependancies between the various plans and to respect the rules of a good man machine relationship. Expert pilots give feedback on the quality and acceptability of the resulting planning assistant. According to their remarks the architecture, mecanismns and knowledge of the Copilote Electronique planners can be tuned. Present scenarios give confidence on the resulting operational benefits of the assistance system.

Dynamic replanning proposals will be demonstrated on a realistic full mission simulator after optimisation of the present mock-up. Real time performances of the resulting planning system will be optimised with the help of current technological progress : a better measurement of real-time constraints for which, for the moment, only provisional precautions have been taken into account in the supervisor architecture mecanismns (for example by adopting "any time" algorithm methodology as in *[Thierry SALVANT 1997]*) . But our belief is that the key of a successful in flight replanning assistance is to keep an approach equally dependant on the pilots cognitive abilities acquisition and on hardware/software evolution.

The first steps of the Exploratory Development phase confirms that the distributed architecture and the Human driven design approach are good drivers for success..

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# The Crew Assistant Military Aircraft (CAMA)

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## 1. SUMMARY

Clumsy automation is considered to be a major reason for deficiencies concerning the interaction between cockpit crew and aircraft systems. Cockpit assistant systems are being developed in support of human-centered automation.

In this paper a general survey on the principals of cockpit assistance will be given. Demands and requirements for an appropriate automation and a functional structure of an knowledge-based assistant system will be introduced, leading to the knowledge-based assistant system CAMA (*Crew Assistant Military Aircraft*) which is presented. The realization of CAMA and its functional units – the modules – are described.

## 2. INTRODUCTION

In future combat transport aircraft, constraints created by low level flying in a high risk theater, the high rate of change of information and short reaction times required will produce physiological and cognitive problems for pilots. From the cognitive point of view, low level flying over rapidly changing terrain elevation coupled with complex and dynamic tactical environment will result primarily in difficulties to maintain situation awareness. It still seems impossible to ensure the pilot's situation awareness as the dominating requirement for high level mission performance and safety.

The central idea of a crew assistant is, to ensure that the crew will have all necessary and useful information and is acting under normal load condition, according to human-centered automation [1]. Design criteria, which aim at a cooperative function distribution between man and machine like that of two partners [2] have to be established.

Both man and machine are active in parallel by assessing the situation and looking for conflict solutions at the same time. In contrast with current man-machine interaction, both assist each other while heading for the same goals. Consequently Billings [1] demands: „Each element of the system must have knowledge of the

others' intent. Cross monitoring (of machine by human, of human by machine and ultimately of human by human) can only be effective if the agent monitoring understands what the monitored agent is trying to accomplish, and in some cases, why.“ Hence, the level of understanding what each element of the system is doing should be as high as possible.

Therefore, Onken [3, 4] demands, that knowledge-based aiding systems should comply with two basic requirements:

- (1) "Within the presentation of the full picture of the flight situation it must be ensured that the attention of the cockpit crew is guided towards the objectively most urgent task or sub-task of that situation."
- (2) "If basic requirement (1) is met, and if there still comes up a situation with overcharge of the cockpit crew (in planning and execution), then this situation has to be transferred – by use of technical means – into a situation which can be handled by the crew in a normal manner."

Basic requirement (1) is to ensure situation awareness of the crew. In part, it can be transferred into the functional requirement for the assistant system as of being capable to assess the situation on its own.

Pilot's workload has become a critical issue as the mission complexity has grown. It is particularly desirable to reduce the need to compose the relevant information from numerous separately displayed data. The ability of the assistant system to detect conflicts, to initiate and to carry out on its own the conflict-solving process and to recommend and explain this solution to the pilot, gives the pilot sufficient time to cope with unanticipated events.

This appears to be a situation-dependent, flexible and cooperative share in situation assessment and conflict resolution between the electronic and the human crew member.

Automation, like recommended in the past, seems to be very attractive but it has to be handled with care not to find the pilot out of the loop of conducting the mission and flying the airplane (check „automate“ and come back

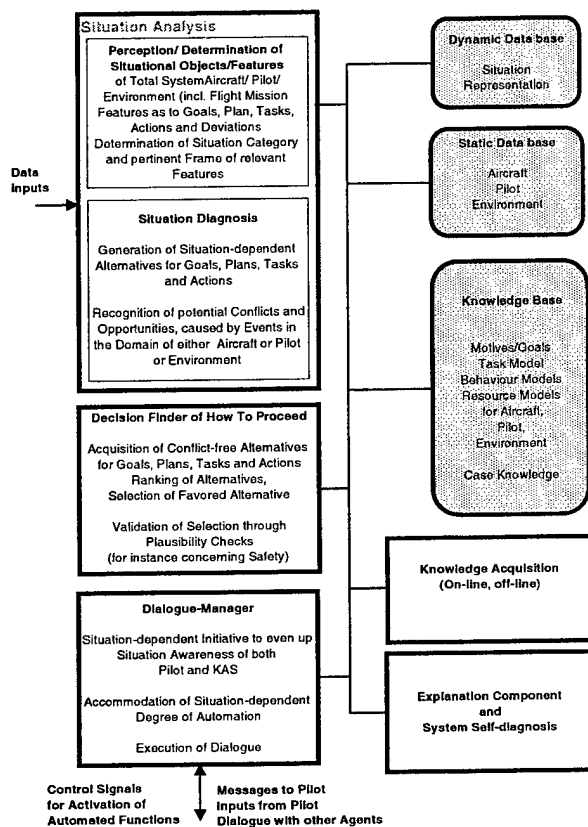


Figure 1: Functional Structure of a KAS

in „manual“ if necessary). Automation as demanded in requirement (2) without the prerequisite of requirement (1) changes the pilot's task into automate management, merely monitoring automatic systems. Increasing workload of the crew should lead to an anticipating of future mission phases and to tasks-execution from that part of the man-machine system, that covers the more comprehensive and accurate situation comprehension for the actual task [4].

These design-criteria and requirements lead to a functional layout of a knowledge-based assistant system (KAS), which is illustrated in Figure 1.

For a comprehensive understanding of the situation, the process of *situation analysis* starts with the perception of features. More abstract objects are derived from these features and assembled to an overall situation description. This closely resembles the human way of situation analysis. On that bases the *situation diagnosis* process recognizes and predicts conflicts from observable indicators, caused by events in the domain of either aircraft, pilot or environment.

Alternatives for goals, plans, tasks and actions are generated including that one, which represents the given flightplan, and all are checked with respect to potential harmful conflicts. If conflicts are detected, only the

conflict-free alternatives are passed to the conflict solver. The conflict solving process is ranking theses alternatives and selects the most favored alternative on the basis of the mission success criteria.

*Dialogue management* insures effective communication with the crew. This, the front-end of an assistant system is to present all necessary and useful information in a way, that is easy to comprehend. Messages to the cockpit crew should be tuned and tailored to the current situation, especially with respect to the resources of the crew. Inputs to the system should allow initialization of services and decision support without tedious or distracting input actions.

Knowledge processing needs a *dynamic object-orientated representation* of the situation-describing objects. The representation covers sensor data as well as very abstract objects like a whole flight plan or for instance the recognized intent of the crew.

Other *knowledge bases* are needed to express and enable access to domain knowledge and to permit inferencing. Models about motives and goals, task selection, execution knowledge and demand for resources as well as behavior models are important examples of this kind of knowledge, executed by additional information about the crew member.

*Static data bases* for navigation purposes or threat data bases can already be considered as standard.

The expert knowledge embodied in the system has to be obtained in a systematic way.

*Knowledge acquisition* appears as the bottle neck during development of the knowledge-based assistant system. Well-defined and efficient algorithms and methods have to be used to cope with the ill-structured and uncertain real world.

In order to increase user acceptance, it is desirable that the system contains a justification or *explanation component*. First of all the user should be conscious of the rules that are applied in the algorithm to obtain a solution or system state to gain confidence to the system. System *self-diagnosis* makes sure that the hints and services to the crew will be really useful. The system must be able to realize, if information concerning the actual situation might be insufficient to assist the crew, or that the system itself is not working all right and needs to be corrected.

### 3. CAMA - CREW ASSISTANT MILITARY AIRCRAFT

#### 3.1 Overview

CAMA (Crew Assistant Military Aircraft) is a knowledge based cockpit-assistant-system for military transport aircraft. It is being developed and tested in close cooperation between the DASA (Daimler-Benz Aerospace AG), DLR (German Aerospace Research Establishment), ESG (Elektronik- und Logistiksysteme GmbH) and the University of the German Armed Forces, Munich. The main challenge of the tactical transport mission are the complexity and dynamic of the tactical situation, the problems yielded by the necessity for a low altitude flight in compliance with a minimal risk routing,



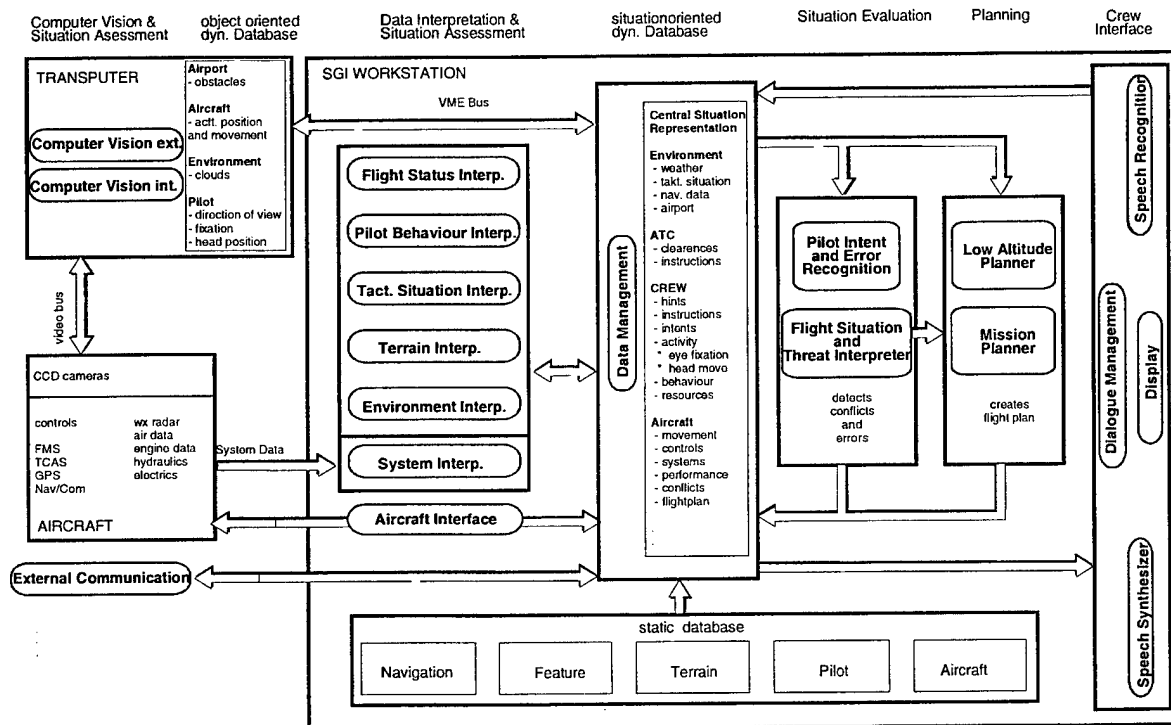


Figure 2. Structure of the Crew Assistant Military Aircraft (CAMA)

terrain collision avoidance, etc., management of fuel and time constraints, e.g. TOT (time over target), and the missing or insufficient establishments of approach aids. CAMA is designed under regard to the requirements, introduced in chapter 1. The realization of the crew assistant will be described in the following chapters.

### 3.2 System Architecture

The system is divided in several functional units, the modules (Figure 2). Each module is responsible for specific tasks. Communication between them is realized via the *centralized situation representation* (CSR). The CSR manages and provides static data and situational information, processed by the modules.

### 3.3 Situation Interpretation

#### 3.3.1 Environment Interpreter

The *environment interpreter* (EI) evaluates the situation concerning weather, navigational aids, air-traffic and flying objects (e.g. SAM). When certain weather events like thunderstorms or clear air turbulences have occurred, it is used as data source for the module *flight situation and threat interpreter* and the module *mission planner*.

#### 3.3.2 Terrain Interpreter

Basing upon the present position and course, the *terrain interpreter* (TI) predicts the trajectory of the aircraft, generates a hyperplane of possible flight trajectories achievable by full exploitation of the aircraft's performance capabilities. Evaluation against a digital

terrain elevation map – basing on digital terrain elevation data (DTED) – detects potential terrain conflicts in front of the aircraft. A recommendation for an effective evasion manoeuvre will be given.

#### 3.3.3 System Interpreter

The *system interpreter* (SI) [5, 6] monitors the aircraft's subsystems (main system, primary flight system, navigation systems, etc.). Any detected malfunction is evaluated by an on board diagnostic to determine it's reason.

#### 3.3.4 Computer Vision External

The module *computer vision external* (CVE) [7] serves for two purposes. The primary job is to support a ILS/MLS like approach even on unequipped airfields. Additionally it detects conflicts concerning obstacles on the runway. Multiple sensor data, like gyros, accelerators, GPS, etc. are used for aircraft state estimation. Additionally a camera-system is used to determine the relative position to the runway.

#### 3.3.5 Computer Vision Internal

The module *computer vision internal* (CVI) provides information concerning pilot's point of gaze. These are evaluated by a camera in the cockpit's front-panel, to the pilot's opposite. The information, for instance the moving line of sight to a control surface or to a special indicator, could be used to confirm the need for a warning or a hint. Especially with regard to an additional *resource model* that will make modeling the crew more complete, information of eye fixations is essential.

### 3.3.6 Tactical Situation Interpreter

The *tactical situation interpreter's* (TSI) main contribution is the computation of a threat map [8]. The calculation is based upon digital terrain elevation data (DTED) and the threat's models. Particular objects from a given list of tactical elements are regarded as threats such as surface-to-air missiles (SAM) or radar sites. A threat model contains the parameters

- maximum range,
- operationability,
- efficiency along range and
- respective models for threat area overlapping.

Figure 3 shows the principle steps of the algorithm for the threat value calculation.

Due to the characteristics of the threat's radar systems and respective radar shadows resulting from the terrain structure, the altitude above ground up to which an aircraft is not detectable by the hostile radar beams can be derived from the DTED database. Given a certain test altitude a threat value of zero can be assumed below

actions are determined, considering flight plan, local ATC instructions, aircraft and environmental constraints.

### Normative Pilot Behavior

The *normative model* [9] describes deterministic pilot behavior as documented in pilot handbooks and air traffic regulations. Modeling is done primarily within the domain of rule-based behavior, but covers admissible tolerances also. Pilot behavior can be separated into situation assessment and action processing components. Modeling is done for all flight segments (taxi, takeoff, departure, IFR-cruise, tactical flight, drop, approach, landing) and concerns the following tasks:

- a) situation assessment

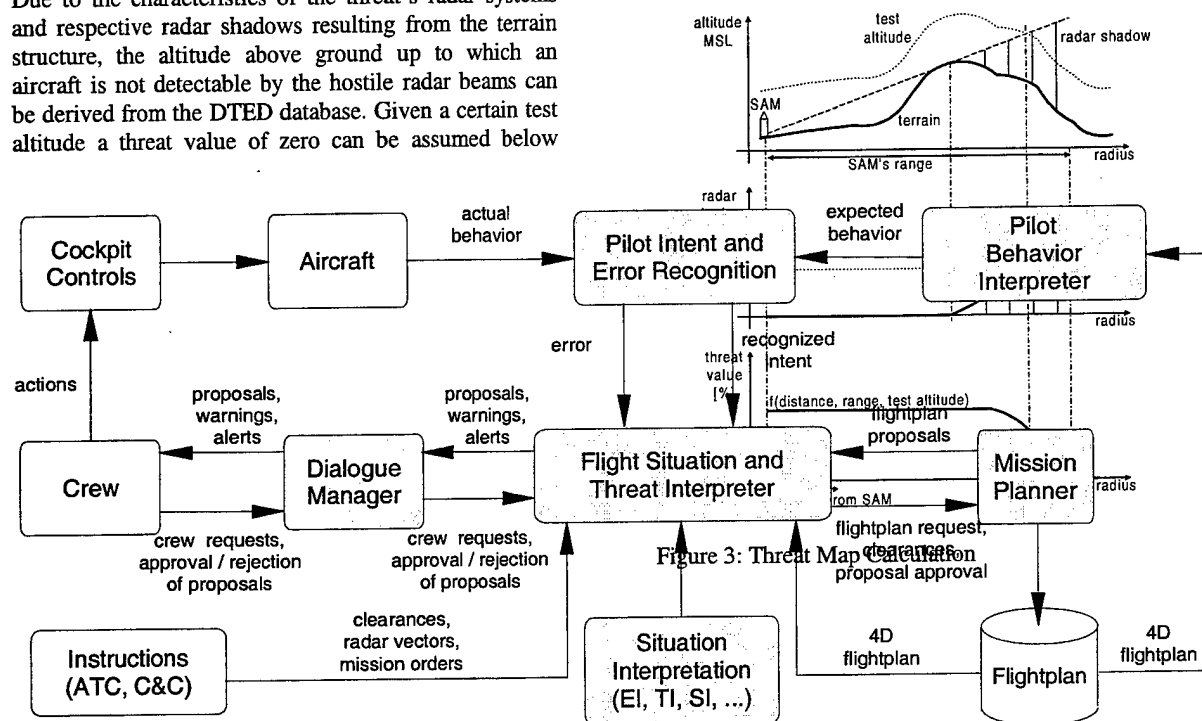


Figure 4: Pilot Behavior Interpretation and Flight Situation and Threat Interpretation

these radar beams. Above the threat value is calculated as a function of the individual model parameter. The threat values are calculated for ten discrete altitudes above ground level (test altitudes every 50 meters in the z-axis) and for each terrain elevation grid point (longitude/latitude coordinates). Area overlapping of threats is taken into consideration by probability calculus.

## 3.4 Pilot Behavior Interpretation

### 3.4.1 Piloting Expert

The *piloting expert* (PE) is constructed as a model of pilot crew and covers normative and individual crew behavior. On the basis of this knowledge, expected pilot

- recognition of actual flight segment
- recognition of process of plan execution related to flight plan procedures
- b) pilot actions / performance
  - primary flight guidance (altitude, course, airspeed, power setting, climb/descent rate, pitch attitude)
  - drop procedure
  - operation of flaps, gear speed brakes
  - operation of ramp
  - radio navigation
  - communication with ATC and C&C

Petri nets were chosen as most suitable for knowledge representation purposes.

### Individual Pilot Behavior

The *normative model* is being enhanced by providing information on the individual parameters. Fundamental

for an adaptive model [10] is the assumption that normative regulations and procedures are still the guidelines, even when they are amended and adapted by the individual pilot.

Normative statements derived from the petri net model are customized in order to achieve a description of individual behavior by

1. varying the transition parameters of the petri net (on-line)
2. varying the structure within a petri net (off-line)

#### 3.4.2 Pilot Intent and Error Recognition

The module *pilot intent and error recognition* (PIER) monitors pilot's activities and mission events in order to interpret and understand the pilot's actions [11]. Expected crew actions are compared with the actual behavior shown by the crew (Figure 4). If discrepancies will be detected the module PIER tries to figure out, whether the deviation was caused erroneously or intentionally. Detected errors are issued to *flight situation and threat interpreter*. Error detection will help the pilot to correct slips and to optimize his situation awareness during committing a mistake by focusing his attention on most important or critical events.

By monitoring pilot actions as well as the mission context, the system is able to compare the pilot's action to a set of behavior hypotheses. In case of an intentional deviation from the flight plan, the module checks, if the behavior fits to the given set of intent hypotheses.

These hypotheses represent behavior patterns of pilots, for example, when commencing a missed approach or avoid a thunderstorm. With the intention recognized, support like re-planning is initiated, and the overall loop could be closed without further inputs of the pilot.

### 3.5 Flight Situation and Threat Interpretation

The module *flight situation and threat interpreter* (FTI) represents the central module of the assistant. It deals with the situation assessment and conflict resolution. The process of *situation diagnostic* and the *decision finding of how to proceed* – recall Figure 1 – are the primarily jobs of the FTI. Situational objects, provided by preceding modules (e.g. EI, TI, SI, etc.), are further processed. The complete image of the situation is evaluated against

- goals,
- plans and
- pilot activities.

Mission dependent goals are derived from the mission order. The mission order comprises instructions and constraints, which are to be kept (e.g. entrance-corridors to gaming area, drop-point, TOT, etc.). Taking into consideration the mission order, the FTI initiates the module *mission planner* (Figure 4) to generate a complete, conflict-free flightplan. If the mission order leads the aircraft into a threatened area, the low altitude flight planner is started additionally for the calculation of a low altitude flightplan as well as a trajectory. FTI controls the planning parameters. They are provided to

the planning modules and comprise origin and destination, corridors to be planned through, civil and tactical waypoints as well as detailed drop procedures. Crew constraints, e.g. personal route preferences are included as well. Generated routes are proposed to the cockpit crew, and are accepted, modified or refused respectively.

Misleading crew intents and errors, recognized by the module PIER are monitored and crew warnings will be initiated. Intentionally, conflict-free deviations are incorporated in the actual flightplan.

Monitoring of the flightplan and evaluation against the situation is done permanently. Conflicts within the planned route, e.g. new threats within the operation area or corridors, weather deterioration en-route or at destination, etc., will be recognized and suitable resolutions are started.

### 3.6 Mission Planning

#### 3.6.1 Mission Planner

The module *mission planner* creates and maintains a 'take off'-to-landing mission flight plan, including routes, profiles, time- and fuel-planning based on knowledge about the mission plan, gaming area, destination, ATC instruction, aircraft status, environmental data, etc. [12]. External data sources ( $C^3$ , weather, results from reconnaissance, etc.) are incorporated into the plan. Events like failures of aircraft systems (navigational equipment, engines, etc.) weather changes and ATC or C&C instruction are taken into consideration. The mission planner covers the flight under instrument flight rules (IFR) as well as time management. Especially with regard to a TOT (time over target), fuel calculations and routes/profiles calculations the mission planner will assist the crew. The calculated route is presented as proposal to be accepted or modified. The 4D trajectory serves as knowledge source for other function blocks.

#### 3.6.2 Low Altitude Flight Planner

The aim of the module *low-altitude flight planner* (LAP) [13] is the calculation of a 3D route between the given planning constraints – controlled by the FTI – with a maximum probability of survival in a hostile environment. This is achieved by avoiding threatened areas if possible, minimizing the exposure to unknown threats and keeping clear of the terrain. Therefore, the planning constraints, the tactical elements and the resulting threat map, the terrain elevation data and the aircraft performance data are taken into consideration. The system consists out of three functional sub-modules:

##### *Danger Analysis*

The *danger analysis* incorporates the threat map calculation as described in chapter 3.3.6. Additionally, the visibility at each point is calculated without assuming any particular threats. The algorithm issues lower danger values on the side of valleys than in the center. Finally, the danger analysis utilizes the calculation of a ground collision probability, which is particularly high in rough terrain. This feature leads to generally higher flight

altitudes in the absence of threats. An overall danger value is calculated for each terrain grid point.

#### *Moding and Control*

The *moding* and *control* checks the flight status and assembles the target point and the planning area for the *optimization* according to the mission constraints. The optimization provides an array of optimal directions to the target point. As long as a re-planning does not imply a new target point another optimization run is not required.

#### *Path Selection*

The *path selection* depends on the current planning mode (initial planning or re-planning). It constructs a terrain grid based flight path from a given start point, respectively present aircraft position to the target point. The *output assembly* functions *trajectory synthesis* and *plan analysis* form the *low-altitude flight planner* output. In order to be monitored by a pilot model based assistant system, the representation of the detailed trajectory has to be reduced to a waypoint based low altitude flight plan, which represents the general considerations to be followed in the human planning of low level missions. Additionally, the low-level flight plan is given by a detailed trajectory representation.

### 3.7 Crew-Interface

Communication between CAMA and crew plays an important role. The kind of information to be transmitted in either direction varies with respect to the different modules. The information flow from the machine to the crew and vice versa is controlled exclusively by the module *dialogue manager* (DM) [14]. The many different kinds of messages require a processing in order to use an appropriate display device and to present the message at the right time. The module *dialogue manager* ranks the output messages and the most important message is issued first. As output devices both, a graphic/alphanumeric color display and a speech synthesizer are used.

More complex information, e.g. the current flight plan, are depicted on a horizontal situation display. The horizontal situation display is an interactive touch-sensitive map display organized in a number of layers which allows the crew to select optional map-presentations in any combination. It allows to depict tactical and threat information as well as a variety of navigational elements and a topographical map similar to the currently used low flying chart paper-maps. A second display contains the alpha-numeric flight-log and is used for in-flight departure-, approach- or missed-approach-briefings.

Commencing the approach to the destination airport, the pilot will be assisted with a combined linguistic and graphical briefing, describing the characteristics and any dangers associated with the approach.

Brief warnings and hints are used to make the crew aware of a necessary and expected action and are transmitted verbally using the speech synthesizer [15].

The input information flow is established by use of speech recognition in addition to conventional input

mechanisms. Intuitive direct *voice input* relieves the pilot of a lengthy and tedious alpha-numerical input task. Voice control seems to be the best solution to deal with mass data. The total on-board vocabulary will be very large and is broken down into sub-sets according to context. In order to improve speech recognition performance, almost the complete knowledge of CAMA is used for contextual decoding to provide situation dependent syntaxes. Thus, the complexity of the overall language model is reduced significantly such that the system can achieve high recognition rates.

The use of speech input and output devices also reflect the idea of human-centered development with respect to effective communication.

### 4. CONCLUSION

The knowledge-based system CAMA improves the crew's situation awareness. Comprehensive situation assessment by the machine in parallel to the crew's situation assessment is realized with subject to a human-centered automation. Monitoring, planning and decision aiding functions provide a safe and successful mission and improve the mission effectiveness.

The actual integration phase of CAMA will end in June 1998 with a man-in-the-loop full mission simulation campaign. After these simulator tests CAMA will be integrated in the experimental cockpit of the ATTAS test aircraft of the German Aerospace Research Establishment (DLR) and will be demonstrated in flight experiments which are scheduled for early 1999.

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# The Cognitive Cockpit: Adaptation and Control of Complex Systems

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## 1. SUMMARY

Automation of human functions in complex dynamic systems produces problems for awareness, dependency, intervention and decision-making. Aiding and support strategies for technological assistance to human decision-making, which embody notions of Human Electronic-Crew (HEC) teamwork, are proffered as alternatives to automation. This paper considers the relevance of control theory as a broad framework for HEC teamwork in dealing with uncertainty in dynamic situations. It examines possible "cognitive cockpit" architectures for future HEC systems, which adapt to both control feed-back and feed-forward requirements, encompassing the uncertainty in dynamic situations.

## 2. INTRODUCTION

Recent developments in real-time data acquisition, fusion, and processing, and in computer modelling and AI modelling techniques (Expert Systems, KBS, Neural Networks), are being used to provide aiding and support for aircrew tasks e.g. Co-pilote Electronique, CASSY Cockpit Assistant, Pilot's Associate technologies. These Human Electronic Crew technologies aim to enable better management of aircrew workload, and to enhance situation awareness (SA). Ambitiously, they aim to improve the quality of decision-making in uncertain situations by involving both the human and computer system components in the performance of cognitive tasks and functions i.e. joint cognitive HEC systems. The potential for co-operation is achieved by incorporating a model of human decision making and control abilities into the control automation, by monitoring pilot performance and workload through behavioural and physiological indices, and by predicting pilot expectations and intentions with reference to embedded knowledge of mission plans and goals.

These ideas have led to the need for greater scrutiny of the specification of cognitive requirements, candidate cognitive architectures, and appropriate cognitive engineering principles for such joint HEC cognitive systems. Paramount among these concerns are the particular requirements for control, dynamic function allocation (DFA), and computer autonomy in such complex HEC systems, with important implications for human command, authority, trust, feedback, and error rectification.

One area of practical work on the control issues has been to seek interface solutions through pilot selectable levels of autonomy (LOA) for functions, governed by the required pilot operational relationship and interaction.<sup>[1]</sup> Discrete LOA modes have been proposed (Inactive, Standby, Advisor, Assistant, Associate), based on Sheridan's taxonomy, with tailorable functional clusterings for flexible responding, to avoid too rigid automation imposed by design. In Associate mode, under full DFA, the proposed

system maintains advisory functions and accepts pilot allocated tasks, but also takes over tasks as the context demands. These modes aim to provide bounded, communicable structure for delegated levels of authority, minimising mode confusion, and building trust and confidence. But the required control structure should not be cognitively complex. Pilots tend to view EC autonomy simply as either automatic, with or without status feedback; semi-automatic, describing what will happen and asking permission to proceed; or advisory, providing information only.<sup>[4]</sup>

## 3 AUTOMATION AIDING EXPERIMENTS

### 3.1 Co-operation and Compensation

Control problems arising from poor mode awareness are commonly reported with complex flight-deck automation systems. In recognition, experimental work has examined the logic or rules for automatic invocation of levels of aiding, to maintain pilot skill and avoid complacency e.g. cyclical invocation.

Following this research paradigm, an investigation of awareness of levels of flight automation aiding was varied was reported at the 3rd HEC workshop<sup>[3,4]</sup>. Using the NASA Multi Attribute Task (MAT) adaptive automation simulation software, failures were introduced in the ability of the automation to intervene in a timely and appropriate manner, with regard to the prevailing task demands. The invocation logic was manipulated to be either logical (co-operative, reducing workload), simulating normal aiding, or illogical (uncooperative, increasing workload), simulating automation failure. The results showed that manual compensation generally equated performance across the conditions but without awareness of the automation failure, indicated by subjective measures. Monitoring and tracking of the status and functioning of aiding with automatic invocation is difficult to achieve. Design safeguards would be needed to prevent unacceptable unpredictability with variable function allocation, and to minimise inappropriate allocation e.g. establishing operator willingness to accept aiding. Recent research at the University of Minnesota has shown how an acceptable invocation logic can be based on significant critical events in the mission situation, e.g. avoiding obvious hazards i.e. mission context sensitive.

### 3.1 Control Feedback Awareness

The MAT adaptive automation simulation software, comprises three task elements, namely manual Compensatory Tracking (CT), Systems Monitoring (SM), and Resources Management (RM). SM and RM tasks were operated in manual, semi-automatic, or fully automated modes. Task aiding is invoked automatically, with on-screen caption warning and feedback on mode change and status. The basic MAT battery provided no explicit differentiation between manual, automatic and

environmentally induced screen changes. Automation functioning has to be inferred from understanding of the control rules.

To investigate more intuitive, cognitively compatible (CC) iconic displays of automation status a followup study, with a modified version of the MAT battery display screen was created<sup>[5]</sup> (Figure 1). It was considered that a familiar, dynamic physical instantiation of automation functioning, using icons with properties of agency, might assist in understanding automation status. In the modified MAT battery, automation activity was represented using dynamic visual icons, depicting the form and location of control actions. Droid-like, R2D2 characters emerged when the automation was invoked. These Adaptive Iconics (AIs) were re-positioned and animated beside SM parameters and RM functional elements, where the automatic action was perceived as taking place. An experiment with 20 non-aircrew compared performance with the original and AI-modified MAT task. Subjects flew task profiles with increasing frequency of events requiring actions, with logical and illogical aiding invocation. Ratings of CC using the SRK-related experiential CC-SART measure (Dimensions: Level of processing; ease of reasoning; activation of knowledge), showed enhanced CC by AIs of the RM task (and CT), with improved RM ease of reasoning. However, SM performance was poorer with the AIs. This was interpreted as over-reliance on SM automation with partial aiding, induced by the presence of AIs, without clear indication of their restricted support. AIs improved the cognitive quality of the interface for one rule-based task, but created undesirable side effects on performance and goal tracking for another.

### 3.2 Microworld Uncertainty

The MAT environment provides a "microworld" of flight simulation, where the task situations were both complex, dynamic, and opaque: not everything is visible, and required inferences with uncertainty<sup>[6]</sup>. To examine the structure of the MAT microworld, a 'goals-means' cognitive task analysis (CTA) was performed which classified the individual MAT tasks according to which knowledge structures were being activated, which rules were being applied, and what skills were being drawn upon to perform the tasks. This CTA revealed that performance on the MAT CT task was skill-based, that the MAT SM and RM tasks were both rule-based, and that some knowledge-based performance was possible in the RM task. However, the support provided by the automation was entirely rule-based. Thus, the MAT environment provides only a weak microworld test of automation aiding, restricted to rule-based problems. Accordingly, in order to provide a broader microworld basis for assessing automation aiding, we have developed a modified VAPs C-code version of the ATC Simulation Task, used previously in SA metrics research, adapted to simulate a multi-aircraft military mission (Figure 2). This provides some of the missing navigation, guidance, hazard/threat management, and spatial reasoning task components of real world of military aviation, which is a rich source of uncertainty requiring knowledge-based behaviour. We believe that

uncertainty is a critical feature of microworlds for testing adaptive automated decision aiding. In the real world, for at least the foreseeable future, EC can not know everything. EC will be fallible, no matter how AI 'smart'. EC will need human oversight, checking and directing. This is because the human crewmember will be able to bring knowledge that EC does not possess, such as high level, mobile political and military goals, associated rules of engagement, tolerance of risk, or whatever uncertainties human intentionality brings to the situation.

### 3.3 Prepared Flexibility

The developed military mission microworld is particularly suitable for testing mission planning and automation concepts. Automation of mission planning functions anticipates predictable events and brings forward decisions on the mission time line. In theory, plan automation enhances SA by freeing limited attentional resources for unexpected events. We have sought to measure how *cognitive rigidity* or 'set arising from plan automation' inhibits creativity and responsiveness to changed situations with knowledge-based tasks. In an experiment simulating a multi-aircraft ground attack mission, subjects (30 non-aircrew) were required to control aircraft over a target, and to exit the area safely, avoiding radar detection and enemy aircraft contact.<sup>[7]</sup> Survival was the briefed prime directive. Subjects received different levels of mission support, i.e. ad hoc preparation; automatic planning and mission rehearsal; auto-plan, rehearsal, plus automatic plan execution. Manual override of automatic plan execution was provided, if the subject wished to depart from the plan. Unexpected enemy aircraft eventually appeared presenting a direct threat to all aircraft on the planned heading to the exit gate, thus requiring manual intervention. The results showed advantages for automatic plan generation and execution with no threat aircraft present. However, when the planned route came under attack, rather than freeing attentional resources, the automation produced over-dependence or "blind trust" in the plan, resulting in high losses from enemy contact (Figure 3, 4). Subjective ratings (SART, CC-SART), indicated poor threat awareness with plan automation. Subjects exhibited delusion of control, rigidly interpreting experience through cognitive schema set by the plan. The expected lag in recognition of the changed situation, normally ascribed to schema refinement, appears exaggerated by plans, causing extended awareness hysteresis. Active involvement in plan generation and execution, provides better adherence to directives, enhanced goal awareness and better strategic control. Plan automation creates a form of goal blindness: failure to see the goal for the plan. Therefore, immersive planning and rehearsal technologies, and assertive automation, should be implemented with caution. Mission support should help to prototype and critique responses to unexpected events. A more useful focus can be on aiding decision-making when the plan breaks down, and on supporting reactive re-planning. This should be done in ways that explain and critique plan options rather than that provide a potentially rigid mind set. Essentially, what is needed is decision support that can break an inappropriate mind set, without substituting another i.e. keeping the pilot in control.



#### 4. COGNITIVE CONTROL

Team function allocation may be appropriate for controlling systems with discrete, bounded, naturally separable functions and tasks, where any resultant autonomy does not significantly threaten goal maintenance. With ill-structured problems involving uncertainty, function allocation needs to be flexible and dynamic with good communication between team-members. Mature human teamwork involves good communication, function and leadership initiative turn-taking, with a transition of authority that is smooth and flexible. The locus of control is driven more by situation and context, than by the preservation of a sole source of control authority. Aiding technologies should use such frameworks to support the pilot efficiently and unobtrusively in achieving the mission objectives, while allowing the pilot to remain at the top of the system control hierarchy, with the ultimate responsibility for generating and setting goals and directives i.e. staying in charge. Goal tracking and control feedback seem to be the key to success.

However, as tasks become more about thinking than doing - more cognitive than physical in nature - the validity of applying team function allocation has to be questioned. Analysis of cognition into separable functions, which become candidates for automation, may be counter-productive e.g. mission planning. In joint cognitive HEC systems, cognitive control may benefit from a functional architecture with integration, rather than segregation and allocation, of high level functions.

In considering cognitive functional requirements, candidate cognitive control architectures, and engineering principles for HEC systems, it is our belief that a principled approach must be taken, based upon, guided by, and hence traceable to theory. For this reason, we have sought to develop an approach to test extant theory on the cognitive control of complex systems. The ideas of Rassmussen<sup>[8]</sup> concerning the reduction of human error in the control of complex systems have been particularly influential. This provides an error-based classification of behaviour with skill, rule, and knowledge levels of performance corresponding to decreasing levels of familiarity with the task or environment, or expertise (Figure 5). Thus, behaviour is driven by both goals and by experience. This approach recognises that humans are (and should be) allowed to be flexible and variable, and so error observability and reversibility are important features for safe task and system design. It is not clear how control is passed between SRK levels.

To account for this and the orderliness of human action, beyond a stored programme, Hollnagel<sup>[9]</sup> considers that control of actions to achieve goals exists on a continuum of modes, with different planning horizons, determined by competence (c.f. experience) and context, rather than procedure. These modes range from scrambled, opportunistic, to tactical and strategic cognitive control modes with increasing levels of depth in the evaluation of outcomes with reference to goals.

Brehmer<sup>[10]</sup> has argued that in dynamic systems, the observability of the system state and the possibilities for action affecting the state of the system are key properties of the system to be controlled. The goals and models of the system are properties of the controller or decision-maker. A system may be controlled by a feed-forward or feedback strategy, or by some combination. In feedback control, the controller uses only current information about the actual state of the system. In feed-forward control, the controller uses a model of the system to predict its state and to select the appropriate control inputs. Feedback control is effective when there are no significant feedback delays in the system, when the system changes over time and no stable model of the system can be constructed. Feed-forward control requires that the system is stable, so that the model remains valid. Applications of control theory in the automatic control of systems often rely on the model to produce the actual control inputs and use feedback information to update the model. Feedback control is cognitively simpler, and is the preferred mode of control in dynamic decision tasks. This works if the rate of change in the controlled system is slow enough for the feedback information to be processed. Hollnagel<sup>[11]</sup> argues that if there is too much information for the controller to process, then the response will be delayed and the performance will deteriorate. Humans can use heuristics to gain time, but the feedback becomes less precise. Here, it becomes desirable to rely more on feed-forward and to anticipate responses. It is important that the joint cognitive system retains control of the process rather than being controlled by it, and that the required stable equilibrium is obtained by a judicious blend of feed-forward and feedback control.

In consideration of the importance of supporting pilot SA through HEC systems, we have sought also to adapt Perceptual Control Theory<sup>[12]</sup> as a theoretical driver for this area of research. Figure 6 shows the Integrated Model of Perceived Awareness ConTrol (IMPACT). The main tenet of this particular model is that SA, or the individual's perception of it, is controlled by behaviour. The model interprets behaviour as an attempt to minimise the difference between desired and actual SA. It has four main constituents: a Perceived Level of SA [P]; a Desired Level of SA [D]; the User's Behaviour [B]; and the Environment [E].

The model works as a basic closed-loop feedback system with a comparator incorporating the feedback in attempting to achieve the goal state. If an individual has a demand for a higher level of SA, and so increases [D], then when the level of [P] is found to be insufficient, the user will formulate some type of behaviour [B], which the user believes will cause changes in the environment [E] that will decrease the difference between [P] and [D]. For example, if the pilot decides that he wants to increase his SA, [D], with relation to his route-plan then he might select, and check, the digital map situation display, [B], which in effect, changes the environment [E]. The environment [E] then provides the pilot with sensory information, [s], that

changes his perceived level of SA, [P], thus bringing it closer to the desired level of SA, [D].

A concern with the application of the model is how it can be used effectively by an automated system to best support the pilot. There are two main ways the automation can use the information the model contains. Firstly, the model provides a reasonable amount of information on the pilot's sensory input. By analysing what perceptions the pilot is taking into account in the decision process, and the quality of these decisions against closure on the goal, the automation can determine the pilot's informational requirements. Thus, the model will guide communication, and meet the high level requirement of ensuring that the automation provides an appropriate level of information, of an appropriate quality. Secondly, the model provides some explanation of the pilot's behaviour, in terms of goals, and perceptions. The ability to know why an entity is performing a certain action, or series of actions, is an essential component of teamwork. Similarly, if we apply the model to both the pilot, and the Electronic Crewmember (Figure 7) then an information exchange can be modelled, the automation receives information about the pilot, while it also provides the pilot with information about the automation, and its actions. A similar symbiotic structure could apply to human-human team SA.

Overall, the main benefit of this model is to guide communication, and provide information about both pilot and Electronic Crewmember. This leads to an increased awareness, which would benefit many complex decision making processes, especially rapid, reactive re-planning.

## 5. THE COGNITIVE COCKPIT

Synthesising the lessons learned, it seems that goal control is the key to successful teamwork. We have sought to develop an approach to an intelligent H-EC Cognitive Cockpit (Figure 8), designed to be cognition sensitive, compatible, adaptive, and supportive to control of pilot goals, in accordance with cognitive engineering principles. This is done by structuring all automated support using Rasmussen's SRK framework, which ensures both invocation and representation of the automation are cognitively compatible. Using a co-operative perceptual control model, we are developing principles for supporting goal awareness (current & desired) and error awareness (diagnosis & rectification), tailored to SRK requirements, with consideration of Hollnagel's modes of control. For conceptual prototyping, in the current version of the Cognitive Cockpit, feedback and feed-forward information is provided to the pilot through not only AIs, but also through schema-based Goal Balls, indicating action-to-goal effectiveness and risk, and providing a cognitively compatible and ecologically valid representation of uncertainty (Figure 10). SystemCrew Balls represent supplied human versus EC workload against the required workload. Support assertiveness is tailored for goal closure in uncertainty, using tutoring, expert advisor, and critiquing techniques, intended to overcome cognitive rigidity without substitution by EC mind set. This conceptual approach could resolve the conflicting control requirements for

teamwork and autonomy with DFA, by developing a view of EC as an extension of pilot cognitive functioning dealing with uncertainty, rather than as an independent cognitive agent. As a guiding principle, we believe that the concepts within a Cognitive Cockpit should be designed to support intentionality. Intentionality is a description of an internal mental, or cognitive state involving a focussing of effort and attention on the real world, with a high level of situation awareness, and with a desire, plan, or purpose of achieving some externally referenced object, or goal. In Perceptual Control Theory terms it is the cognitive closure between the perception of the current situation and the desired situation. To support intentionality, Cognitive Cockpit work on individual differences (characterology) has indicated that we should be concerned with supporting both insight and responsivity. Specifically it should liberate intentionality, and provide goal, error and control awareness. It should not block intentionality, inhibit nor reverse intentionality, nor second guess. The ultimate aim of the Cognitive Cockpit work is to find the appropriate blend of feed-forward and feedback information for supporting the intentions of commanders and operators, that enables them to be in control of, rather than controlled by, the system.

## ACKNOWLEDGEMENTS

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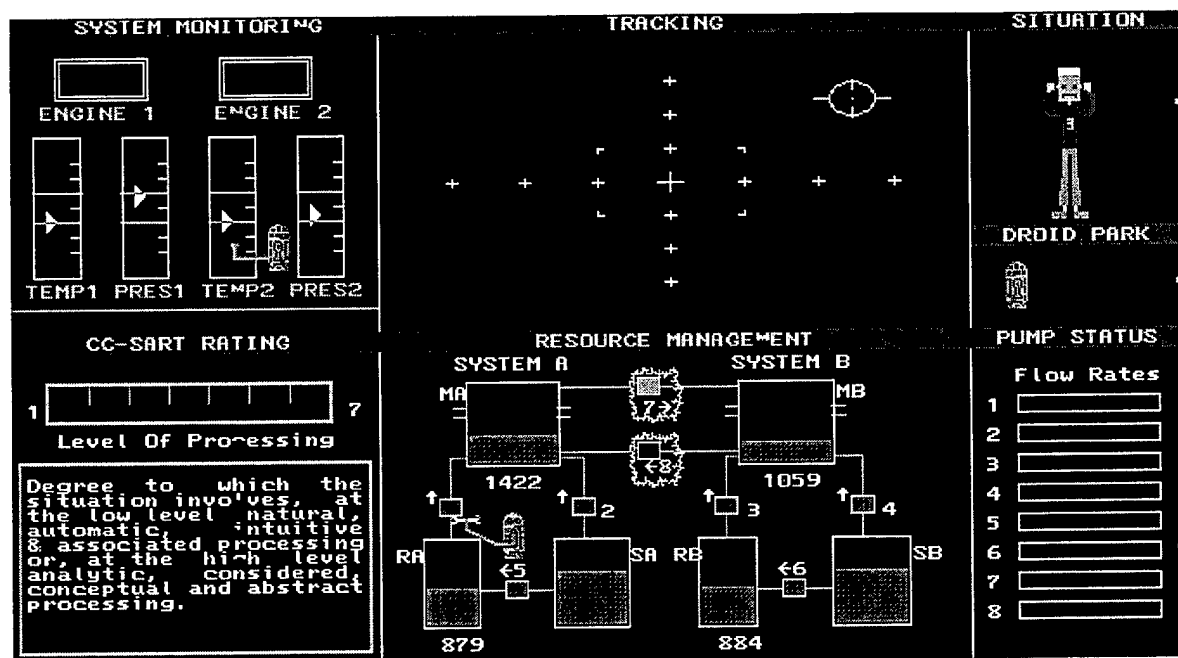


Figure 1 – Modified Version of the MAT Battery

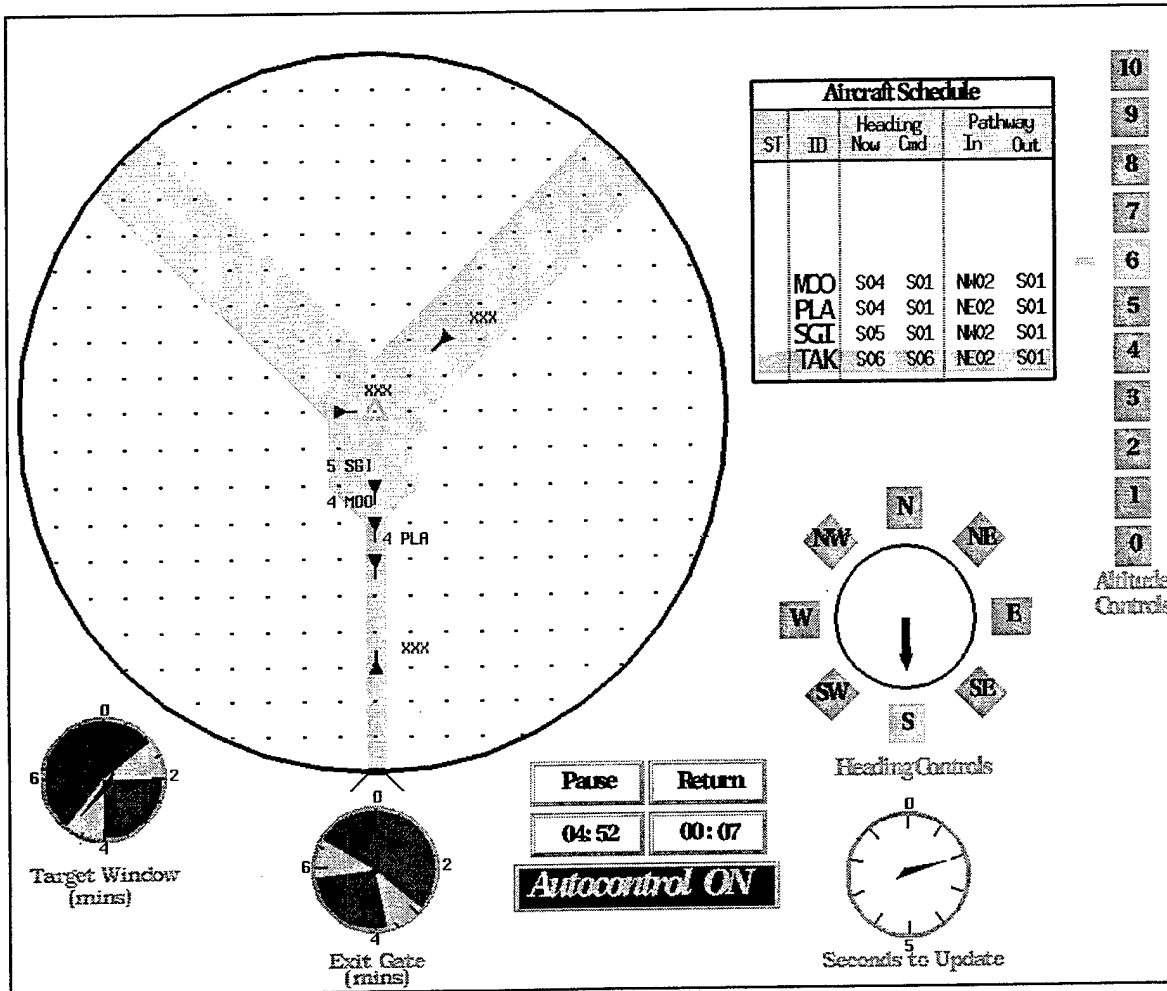


Figure 2-Mission Planning in an Uncertain Microworld

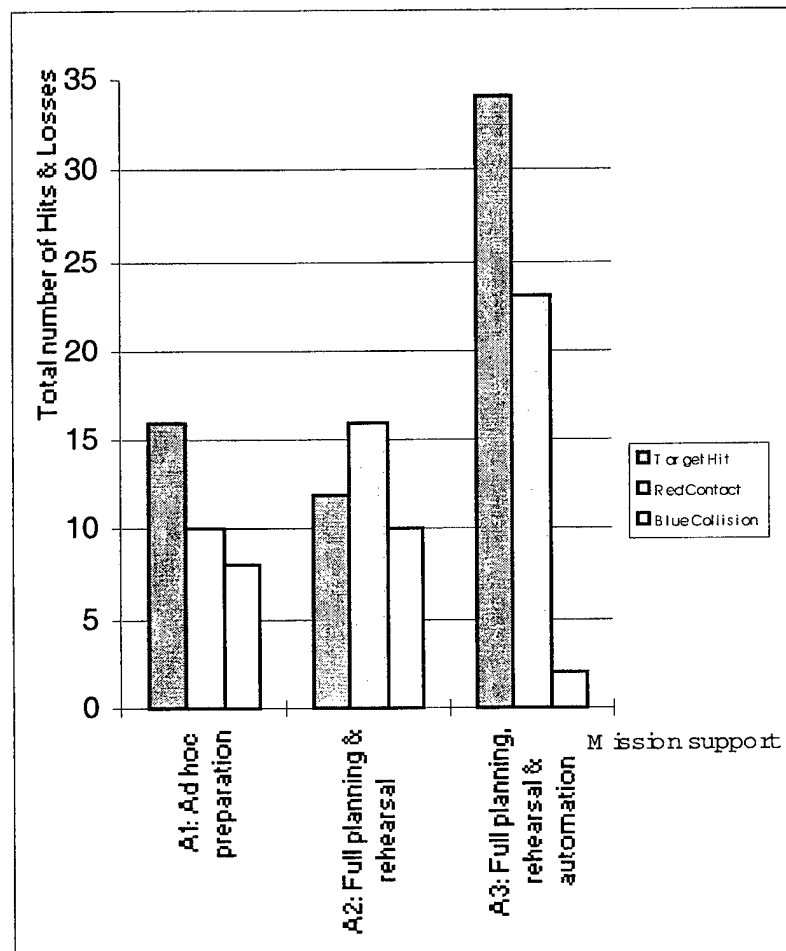


Figure 3-Performance under threat

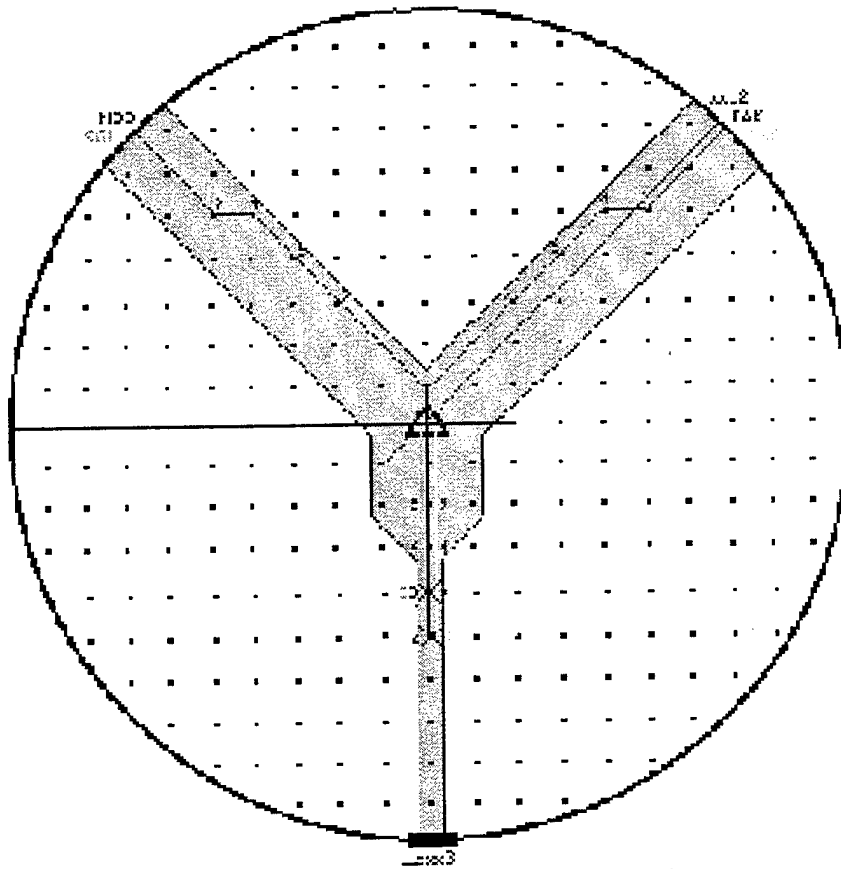


Figure 4-Subject record with Automated Plan Execution



## Perceptual Control of Situational Awareness

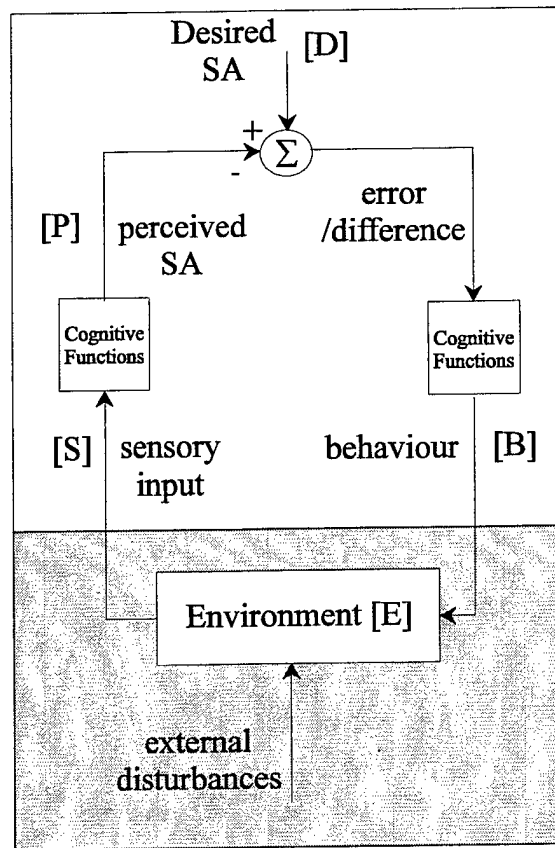


Figure 6 - IMPACT



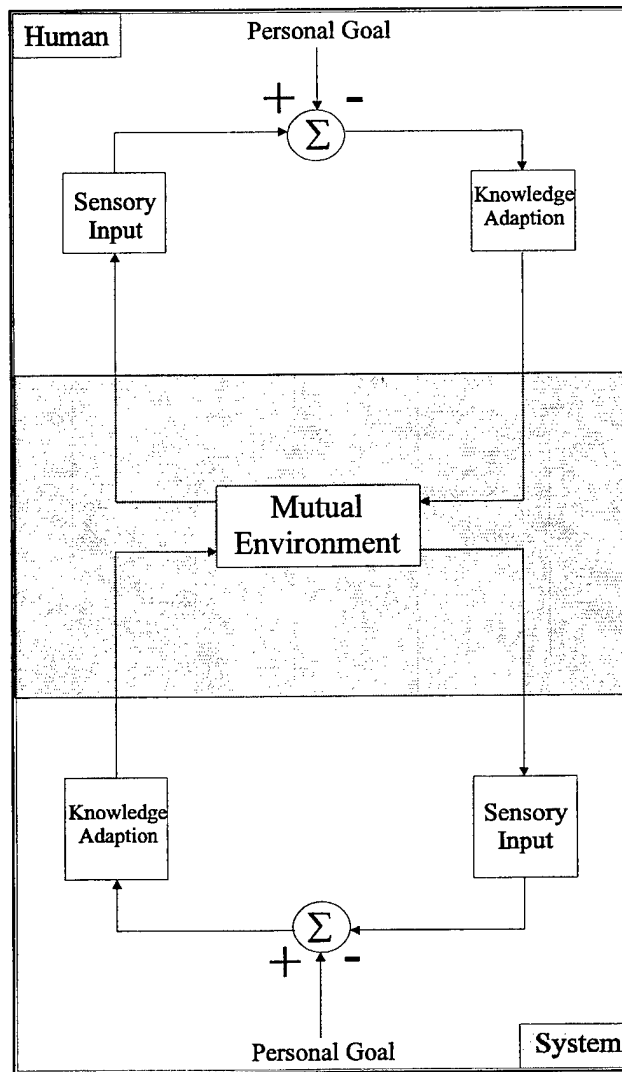


Figure 7 - Joint IMPACT

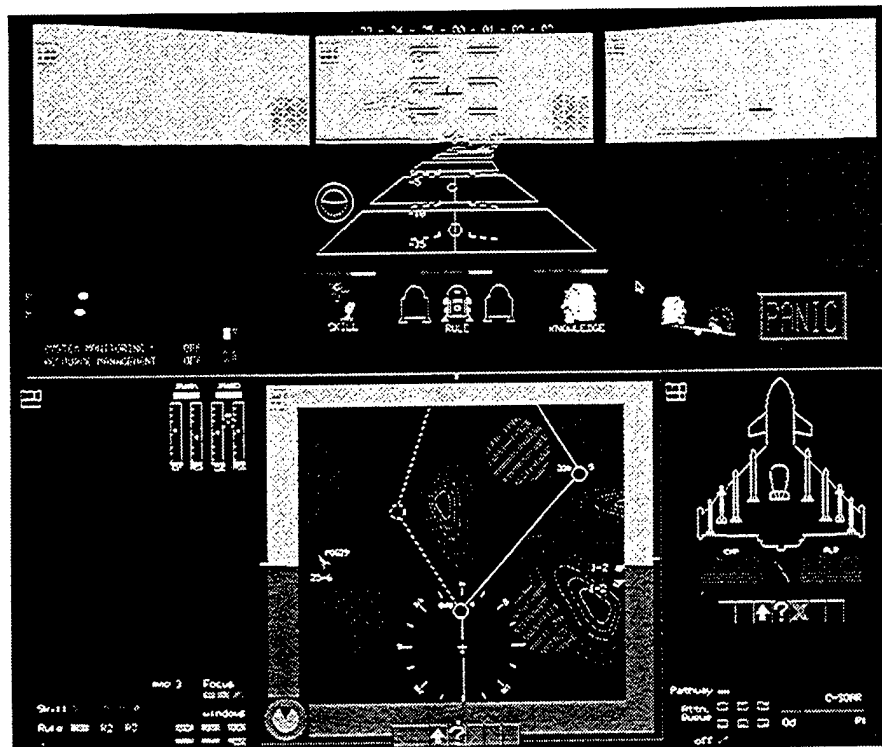


Figure 8- Cognitive Cockpit

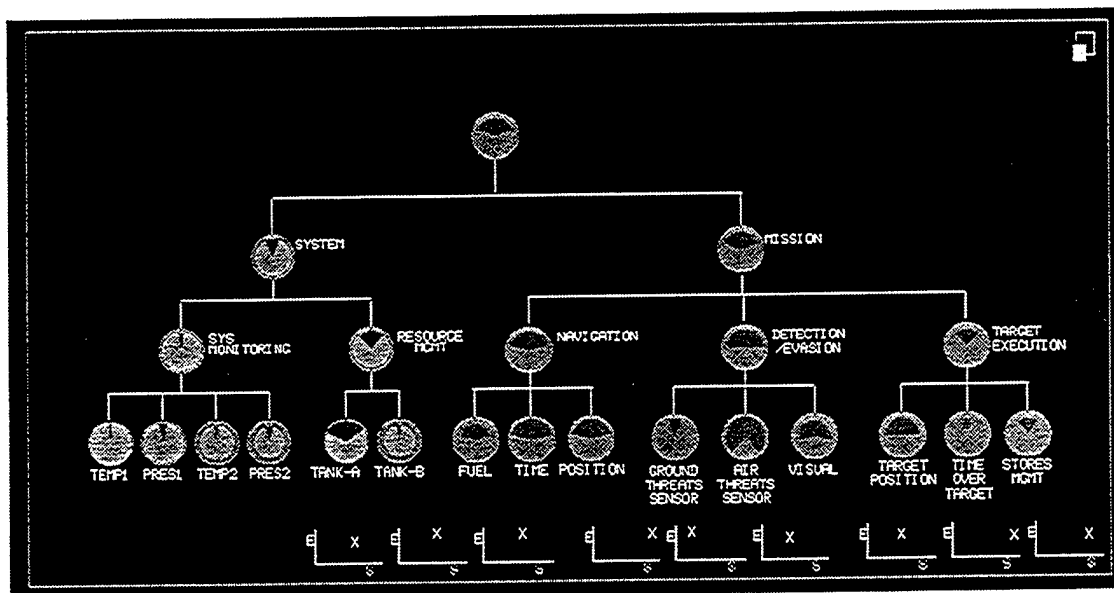


Figure 9 - Goal Balls Hierarchy

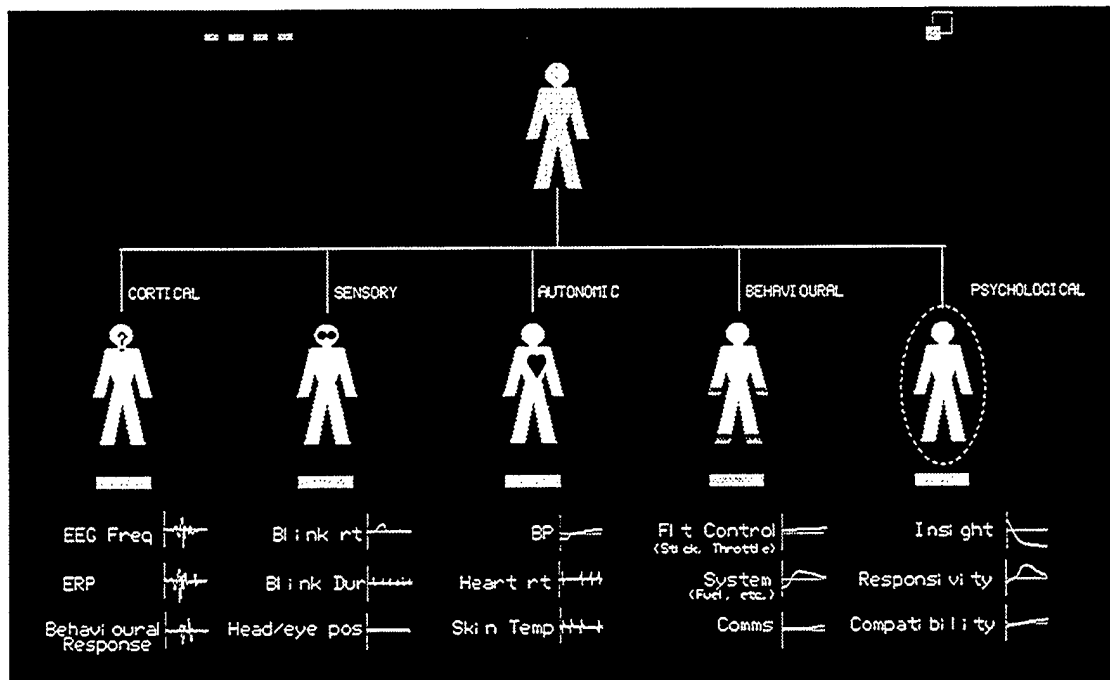


Figure 10 – Health Monitor Hierarchy

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## **Machine Perception as Electronic Crewmember Capability**

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A machine perception system for aircraft and helicopters using multiple sensor data for state estimation is presented. By combining conventional aircraft sensors like gyros, accelerometers, artificial horizon, aerodynamic measuring devices and GPS with vision data taken by conventional CCD-cameras mounted on a pan and tilt platform, the position of the craft can be determined as well as the relative position to runways and natural landmarks.

The vision data of natural landmarks are used to improve position estimates during autonomous missions. A built-in landmark management module decides which landmark should be focused on by the vision system, depending on the distance to the landmark and the aspect conditions. More complex landmarks like runways are modeled with different levels of detail that are activated dependent on range. A supervisor process compares vision data and GPS data to detect mis-tracking of the vision system e.g. due to poor visibility and tries to reinitialize the vision system or to set focus on another landmark available. During landing approach obstacles like trucks and airplanes can be detected on the runway.

The system has been tested in real-time within a hardware-in-the-loop simulation. Simulated aircraft measurements corrupted by noise and other characteristic sensor errors have been fed into the machine perception system; the image processing module for relative state estimation was driven by computer generated imagery. Results from real-time simulation runs are given.

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## Cognitive Architectures for Supporting Strategic Behaviours in Adaptive Systems

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### 1. SUMMARY

This paper discusses the design implications for human electronic air crew systems from the findings of recent research on the cognitive processes underlying the strategic behaviours and decision making of fighter pilots. A research aim was to explore whether Psycognition, a methodological approach which focuses on eliciting the subconscious processes which influence human behaviour, could contribute to our understanding of the cognitive requirements for adaptive air crew systems.

The Psycognition methodology was applied to an investigation of how fighter pilots' subconscious processes influenced their strategic behaviours in handling certain critical incidents. The research focused on pilot's strategic behaviours in three kinds of critical incidents: plan breakdown, control breakdown and information overload. The key findings are:

- Despite the similarities in background, training, experience and the strength of the military culture, there were significant differences in how the subjects reacted to critical incidents.
- In these situations the subjects drew upon deeply rooted subconscious core beliefs to guide their decisions and actions, instead of conscious, rational cognition.
- The differences in strategic behaviours were evident in situations which involved a breakdown in plan or control, an overload of information or a compromise of principles and values.
- Psycognition provides us with a basis for predicting what these behaviours will be, the strategies that will be applied and the breakdown situations in which they will be triggered.

The identification of predictive subconscious behaviours at breakdown points can contribute to our understanding of the human requirements for future cognition adaptive systems. The paper considers the design implications of this research for candidate cognitive architectures for human electronic air crew systems. The consequences for embedding this knowledge (Psycognition) in system pilot models and HEC interfaces will be discussed. The implications of real time intervention through aiding and supporting strategies will be explored.

### 2. INTRODUCTION

Our recent research studied the strategic behaviours of fighter pilots in the handling of three kinds of critical incidents: plan breakdown, control breakdown and information overload. A research aim was to explore whether Psycognition, a methodological approach which focuses on eliciting the subconscious processes influencing human behaviour, could contribute to our understanding of the cognitive requirements for adaptive air crew systems.

Core to Psycognition is characterology, which was the framework used to examine the subjects' core strategies. Characterology refers to the set of core beliefs and emotional responses formed early in development and the strategic behaviours which are predicated on these core beliefs. The framework consists of six types of character strategies. (Ref 1) An abbreviated overview of the characterological types is provided in Table 1.

Table 1: An Overview of Characterological Types

	Orientation	Core Belief	Strategic Behaviour
<i>Mr. Safety*</i>	Safety & trust.	Dangerous world.	Over focused on detail & analysis. Creates own world - excludes external. Information overload: chunk, filter, escape.
<i>Mr. Action*</i>	Performance & recognition.	Self-worth stems from achievement.	Action & perfection. Focus on the logical & rational. Information overload: speed up.
<i>Mr. Endurance*</i>	Indirect control & endurance.	Not good enough but must do one's best.	Subtle influence & control. Bearing up, delaying, resisting. Information overload: queuing & delaying.
<i>Mr. Freedom*</i>	Freedom / control. Be the best / win.	Must be in charge. Not safe to give up control.	Ensures own choices & decisions. Seeks adventure & excitement. Information overload: abstraction, multiple channels, manipulation.
<i>Mr. Self-Reliant</i>	Challenge, going it alone.	Take care of oneself. Never rely on others.	Proving self-reliance. Mobilising self-support. Personal challenge.
<i>Mr. Attention</i>	Getting attention & involvement.	Not being interesting & listened to.	Dramatises events / feelings to get attention & avoid separation.

Table 2: Themes &amp; Patterns in the Subjects' Strategic Behaviours

Strategy	Information Overload	Control Breakdown	Plan Breakdown
<b>A</b> <i>Mr. Safety</i>	Not trusting information. Seeks quantity in order to control overload.	Unsafe not to be in control. Feels unsafe when gives up control.	Focus on manipulating situation to achieve goal. Refusal to give up. Withdraws goal if core values are compromised.
<b>B</b> <i>Mr. Action</i>	Speeds up - faster. Goes for detail.	Increases effort - tries harder. Gives up if doesn't reflect negatively on him.	Focus on what is believed to be right. Perseveres & changes strategic plan. Accepts breakdown if rationally understood.
<b>C</b> <i>Mr. Endurance</i>	Slows / delays things. Does best & waits.	Attempts to understand. Relinquishes control.	Focus on doing his best. Adapts to breakdown. Compromises if necessary.
<b>D</b> <i>Mr. Freedom</i>	Deflects situation through abstraction. Manipulates to maintain control.	Exerts power to control. Superimposes own methods for control.	Focus on achieving what he wants, in his own way. Impulse over-rides rational thinking / judgement. Refuses to accept failed situation.

The research highlighted significant differences between the subjects' strategic behaviours in the three incidents, which led to four particular strategies emerging from the data. (Ref 2) The strategic themes that emerged suggested that each subject drew upon a core strategy to handle breakdown situations. The characterology framework was applied to the examination of these core strategies. This led to explanations for the differences in the subjects' strategies and the similarity in each subject's strategic approach to the incidents. Four of the six characterologies (identified by \* in Table 1) emerged from the data, which was fortuitous. These are summarised in Table 2.

These findings lead us to conclude that the identification of dominant character orientation provides us with a basis for developing hypotheses about the subconscious strategic behaviours that will emerge in certain breakdown situations. This can make an important contribution to our understanding of the human requirements for future cognition adaptive systems.

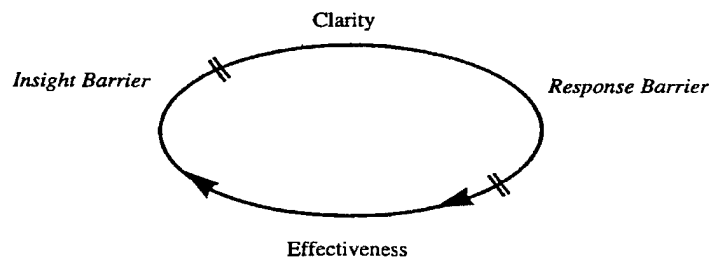
### 3. COGNITIVE ARCHITECTURES FOR ADAPTIVE SYSTEM SUPPORT

The research findings have formed the basis for considering cognitive architectures to support pilots' strategic behaviours. It is our theory that there is potential for cognition adaptive systems to provide pilot support through structuring information, providing control feedback and by handling basic

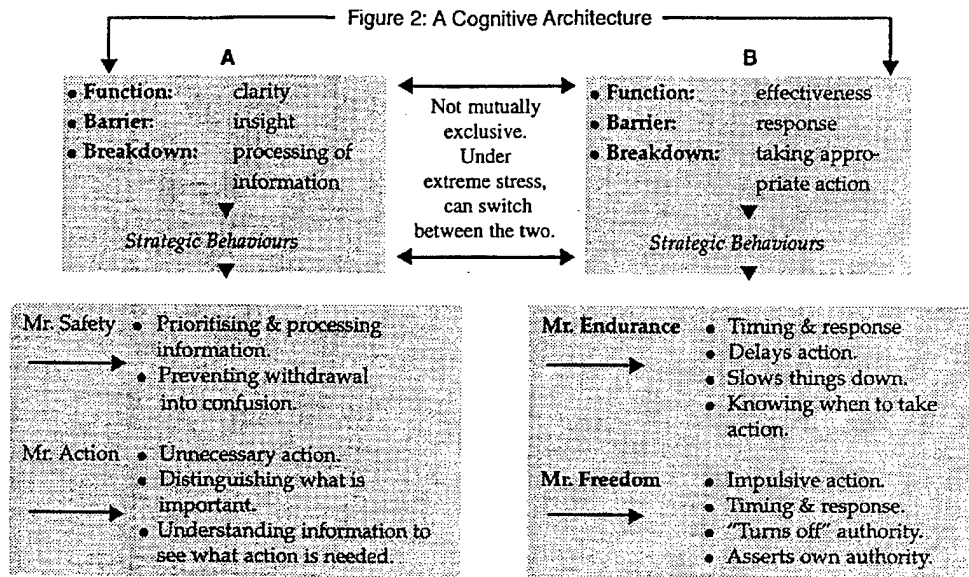
operational functions. The cognitive architecture explored in this paper focuses on the strategic behaviours and barriers that emerge at breakdown points. In breakdown situations behaviours emerge which are intuitive and automatic. When this happens a strategy ceases to be effective, however, individuals will continue with the strategy despite signs it is no longer working. The underlying theory is that by bringing this subconscious behaviour to the forefront of conscious awareness, we are able to interrupt the automatic behavioural process. This leads to more appropriate and effective strategies in breakdown situations.

Our research highlighted the interruption of two major functions in breakdown situations. (Ref 2) The clarity function is interrupted by an insight barrier and the effectiveness function by an action barrier. These two functions which are essential to situational appropriate behaviours, are inhibited by these barriers. The cycle for situational appropriate behaviour begins with the clarity function. Clarity is derived from awareness, attention and information. When an insight barrier emerges, the clarity to move to the next function will be absent and the individual will continue to seek clarity. The effectiveness function is interrupted by a response barrier. When this barrier emerges, the individual will experience difficulty in responding with appropriate and effective action. This process is illustrated in Figure 1.

Figure 1: Cycle for Situational Appropriate Behaviour







### 3.1 A Cognitive Architecture

The interruption of the two primary functions led us to consider a cognitive architecture based on the two breakdown behaviours: the processing of information and taking appropriate action. The cognitive architecture presented in Figure 2 provides a framework for identifying the interventions and support required by individuals who experience these breakdowns. In circumstances when multiple strategies are drawn upon, for example, a breakdown in clarity shifts to a response breakdown, by tracking the individual's strategic process, an adaptive system could switch to the appropriate architecture.

## 4. A MODEL FOR COGNITION ADAPTIVE SYSTEM SUPPORT OF STRATEGIC BEHAVIOURS

The model for supporting the cognitive architecture presented in Figure 3 is drawn from the Psycognition methodology. It is based on the process an expert analyst

would apply in working with character strategy in a breakdown situation. This process was mapped on to a pilot breakdown scenario drawn from the research, to determine how it could be applied to pilots' strategic behaviours. Parts of the process and certain interventions were found to be potentially applicable to the fighter pilot domain.

### 4.1 A Scenario - Cognition Adaptive System Support for Mr. Safety

*Inside the cockpit* : An information overload situation leading to a perceived control breakdown: a plethora of information, inside and outside of the cockpit. Mr. Safety's internal dialogue is running, "How can I avoid being my own worst enemy? Are my priorities right? I'm losing it." He is suffering from distraction, "Why isn't that indicator light changing? Is this information important, can I trust it? Where is the bad guy, enemy radar is squirting something. I must avoid that storm!"

Figure 3: A Model for Cognition Adaptive System Support of Strategic Behaviours

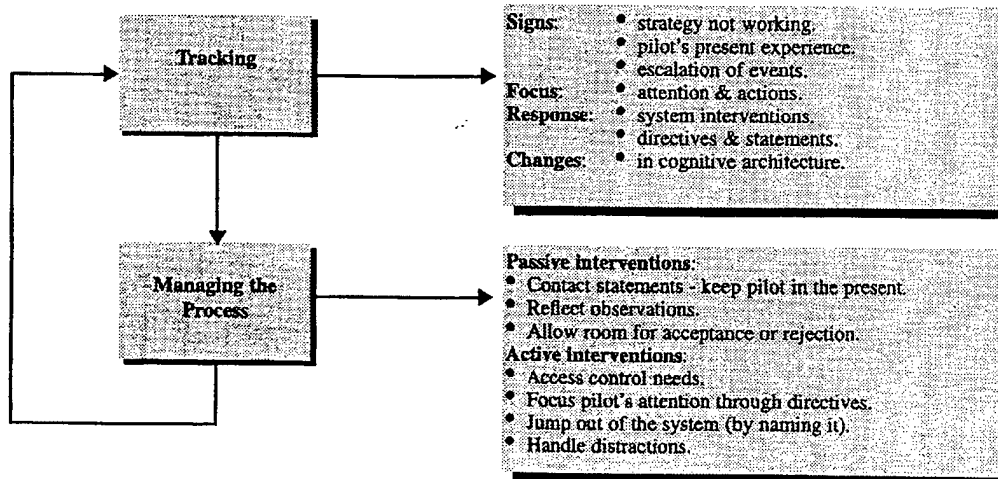
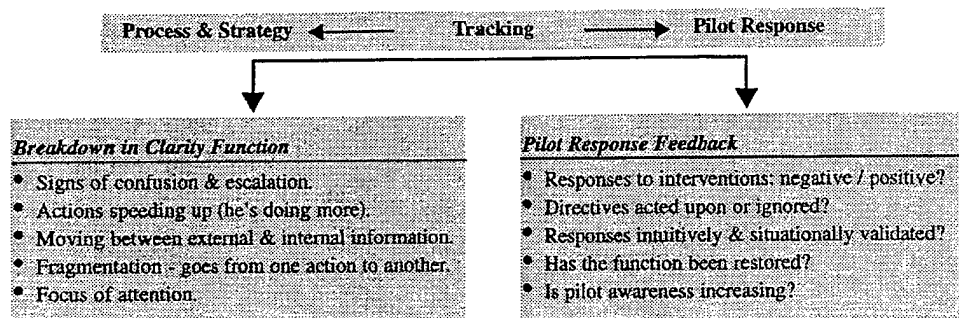


Figure 4: System Tracking Intervention Process



The cognition adaptive system 'knows' the cognitive architecture of Mr. Safety. It has a map of his behavioural strategies for handling a breakdown in the clarity function. The system will track his difficulties in processing information and will attempt to manage the process through interventions to reduce the insight barrier and to restore the clarity function. The system aims to slow things down for Mr. Safety so that he can understand the meaning of the information he is receiving. It attempts to break things into smaller, more manageable steps. It will also try to keep Mr. Safety in contact with the situation to prevent him from withdrawing into confusion or over analysis. The system does this by tracking signs of the strategy not working, which will be reflected in increased confusion and fragmentation. Examples of the system tracking process and interventions are illustrated in Figures 4 and 5.

##### 5. COGNITIVE REQUIREMENTS FOR ADAPTIVE SUPPORT SYSTEMS

- The locus of control must be appropriately balanced between the pilot and the cognition adaptive system. In situations where the locus of control lies with the system, the pilot's internal authority must remain in control.

- The pilot must know which of the system's functions s/he can override and which ones they cannot.
- The system must support and not inhibit rational intentionality. ("It doesn't make sense to me, but you must have a good reason.")
- The system's interventions and behaviour must not contribute to the information overload or control breakdown. This will require close monitoring of the system impact on the pilot to determine when the interventions are helpful and when they are contributing to the problem.
- The relationship between the cognition adaptive system and the pilot needs to be well established outside of the cockpit.
- The cognition adaptive system's understanding of the pilot's cognitive architecture and behavioural strategies needs to be built up over a period of time. Initially, this understanding would be developed outside of the cockpit. However, it is essential that it is developed further through adding behavioural information collected during each mission.
- There must be a high level of compatibility between the system and the pilot. This depends on the system supporting the appropriate cognitive architecture and on it's ability to switch to a more appropriate architecture if the pilot's behavioural strategy changes.

Figure 5: Mr. Safety Intervention Scenario: Control Breakdown & Information Overload

Managing the Process: <i>Organise the speed by slowing down &amp; focusing. Simple precise &amp; prioritising interventions.</i>	Intervention & Feedback Function
<p>Take a moment, slow down &amp; focus.</p> <p>What would help you to regain control right now?</p> <p>It seems like more information at the moment is not useful.</p> <p>What kind of information would be useful to you right now?*</p> <p>You have all the information you need for the moment.</p> <p>Let's stop &amp; consider what the priorities are.</p> <p>You're doing fine, slow down and focus.</p> <p>This is what is important.</p>	<p>Joots: naming the system</p> <p>Focus: present &amp; needs</p> <p>Contact: maintain contact</p> <p>Prioritise: important information</p> <p>Joots: naming the system</p> <p>Prioritise: priorities</p> <p>Joots: system naming</p> <p>Support: choice</p>
Handing over: Support Function <i>I'm keeping an eye on this so you don't have to.</i>	Pilot Validation & Acceptance Criteria
<p>Let me handle the distractions so that you can focus.</p> <p>I'll keep my eye on the red light so you don't have to.</p> <p>I'll tell you when the fuel level changes.</p> <p>I'll remind you when to turn the radio back on.</p> <p>I'll take control, you check the plan.</p>	<p>Will I be more or less in control?</p> <p>Do I need to or can I trust the system?</p> <p>Can I trust the system?</p> <p>Can I trust the system?</p> <p>Can I trust the system?</p>

*Offers three/four categories of information: e.g.*

*Pilot pushes button to select one: ground control, weather, electronic warfare, status of the cockpit.*

## 6. DESIGN IMPLICATIONS

An important implication of the cognition adaptive system scenario is the uncertainty around the behaviours that could result from the system interventions. Although the system intention is to evoke appropriate behaviours, instead it could lead to an increase in inappropriate behaviours.

In the scenario described above, the pilot's behaviour could be accentuated instead of diminished. For example, his reactions could lead to increases in delay, disorganised action, fragmentation, confusion and impulsive action.

System interventions could also inadvertently trigger core belief behaviours. For example, resistance, power, control, safety and trust. These implications need to be carefully researched.

The interpersonal dynamics between the system and the pilot will determine how effectively a system can provide cockpit support and guidance. Therefore the dynamics that could develop from different system interventions need to be carefully researched.

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# "Tasking" Interfaces; Associates that Know Who's the Boss

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## 1. SUMMARY

Despite substantial technological success, "associate" systems continue to suffer from a fundamental, sociological problem—namely, that human operators of advanced automation are used to being in charge. We have recently begun adapting techniques from our associate research to the construction of "tasking" interfaces which enable the kind of interaction operators are used to having with intelligent, informed subordinates. Instead of being autonomous, or even truly mixed-initiative, "tasked" systems are always subordinate—but they know enough about the tasks in the domain that instructing them is vastly easier than instructing traditional automation systems. We use a shared task model to give advanced automation systems (e.g., Unmanned Air Vehicles—UAVs) the same task and goal understanding that the human has. When combined with a planner, the resulting system permits 'tasking' at all the various levels an intelligent subordinate should be able to accept: exhaustively specified plans to be performed exactly, partial plans which leave the planner free to create any full plan which includes those pieces, constraints which require the planner to stay away from certain methods or resources, or high-level goals for the automation to achieve however it thinks best. The net result is a human-machine system which is almost as capable as an associate, and which reduces human workload almost as much, yet which leaves the human more in control than an associate does.

## 2. INTRODUCTION—THE PROBLEM

In the approximately 12 years since the first associate systems were conceived and development work was begun, workers in the field of human-electronic crewmember systems have achieved an impressive array of technological successes. Numerous working prototypes have been demonstrated and are beginning to find their way into common use. The field has expanded far beyond its initial beginning with associates for fighter pilots, to encompass commercial aviation, automobile driving, oil refinery control room applications, etc. The U.S. Army is on the verge of flight testing its Rotorcraft Pilot's Associate and even Microsoft's latest Office™ products are shipping with a task-based, intent-tracked help system.

In spite of these technological achievements, experience has consistently shown that the concept of a human-electronic crewmember, as it has been implemented to date, suffers from a basic sociological problem. Namely, pilots (and other human operators of complex systems) want to remain in charge of the equipment they use. In developing the Rotorcraft Pilot's Associate Cockpit Information Manager [1], we interviewed a variety of rotorcraft pilots and RPA designers to develop a consensus list of prioritized goals for a "good" cockpit configuration manager. Two of the top 3 items on the

list were "Pilot remains in charge of task allocation" and "Pilot remains in charge of information presented."

By definition [2], and for good reasons, an associate system shares responsibility, authority and autonomy over many cockpit behaviors with the human operator(s). This is especially true of the traditional associate behaviors of information management and adaptive automation. It is important to remember, however, that the motivation for creating associate systems which had the capability to share these tasks with the operator has always been to reduce operator workload and information overload [3]. While operators wish to remain in charge, and it is desirable that they do so, the simple fact is that in today's complex systems, operators cannot be fully in charge of all system operations—certainly not in the same way they have been in earlier cockpits and workstations.

Conceptually, the problem can be presented as in Figure 1. This figure shows the relationship between the adaptiveness of a human-machine system as a function of the workload or unpredictability it causes for the human operator.

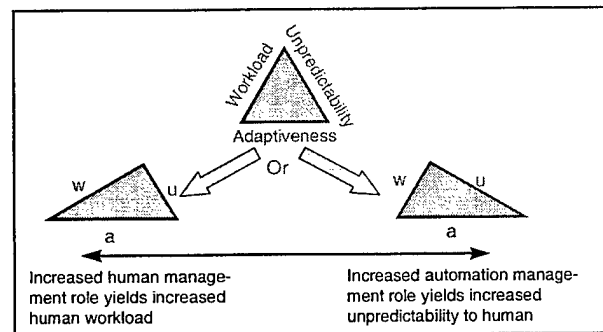


Figure 1. Conceptual view of the relationship between system adaptiveness, human workload and unpredictability to the human operator.

The implication of this view is that for any increase in adaptiveness (that is, the ability of the human-machine system to perform in an appropriate, context-dependent manner in different situations) there must be an accompanying increase in either human workload (the amount of physical, attentional or cognitive "energy" the human must exert to use the system) or in unpredictability for the human operator (inability of the human to know what the automation will do at any given time). Since adaptiveness is generally the goal of added complexity (though systems can be complex without achieving this goal), this is equivalent to saying that any increase in human-machine system complexity must affect the human operator in two ways—either (1) the added complexity must be fully controlled by the human, resulting in increases in human workload, or (2) the added complexity must be managed by automation, resulting in increases in unpredictability

to the human. These alternatives represent endpoints on a spectrum; many intermediate points are possible.

Associate systems have chosen to address the problems incurred by increased adaptiveness by adding an extremely sophisticated suite of cockpit automation. Thus, they are near the "automation" end of the spectrum of solutions. When successful, they do obtain the benefit of greatly enhanced system adaptiveness with little or no increase in human workload. But they continue to encounter the socio-technological hurdle of diminished control and increased unpredictability for the human operator.

In the remainder of this paper, we present initial work on a solution which allows human operators to interact with advanced automation at a variety of levels. While this does not eliminate the dilemma presented in Figure 1, it mitigates it by allowing operators to flexibly choose various points on the spectrum for interaction with their automation. We call human-machine systems of this sort "tasking" interfaces, because they allow posing a task to automation at all the different levels one might "task" an intelligent, knowledgeable subordinate. The notion of tasking gives the operator the same type of control s/he currently has over tasks delegated to subordinates, thus it provides him or her with a greater degree of control than a full mixed-initiative associate system does, while allowing low workload interactions in situations where they are desirable.

### 3. PROPOSED SOLUTION—TASKING INTERFACES

Figure 2 presents our general architecture for tasking interfaces.

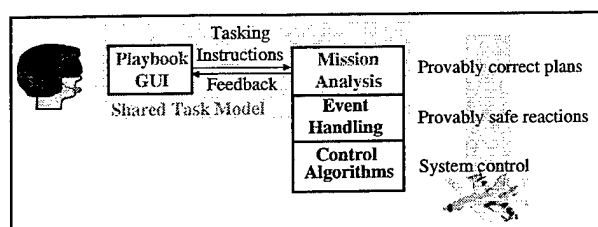


Figure 2. General Architecture for Tasking Interfaces.

The primary components are a Graphical User Interface (GUI) and a Mission Analysis component which are based on and communicate with each other and with the human operator via a Shared Task Model. The human operator communicates tasking instructions in the form of desired goals, tasks, partial plans or constraints in accordance with the task structures defined in the shared task model. These are, in fact, the methods used to communicate commander's intent in current training approaches for U.S. battalion level commanders [4]. The Mission Analysis component is a projective planning system which is capable of understanding these instructions and (a) evaluating them for feasibility and b) expanding them (where necessary) to produce fully executable plans. Once an acceptable plan is created, it is passed to an Event Handling component which is itself a reactive planning system capable of making moment by moment adjustments to the plan to enable execution. The event handling component then passes these instructions to control algorithms which actually effect behaviors in the controlled sys-

tem automation. Since the Playbook GUI, Mission Analysis component and the Shared Task Model are components unique to the construction of a tasking interface, as well as the focus of our current research, they will be described in more detail in separate subsections below.

### 3.1 Shared Task Model

The enabling technology for a tasking interface is the ability to code, track and dynamically modify the plans, goals, tasks and objectives which one or more humans may have in operating their automation and equipment. By explicitly representing such a "task model" in a format that is both familiar and recognizable by a human operator *and* which is interpretable by a knowledge-based planning system, we gain a level of coordination between human and system beyond what was previously possible. Work on the U.S. Air Force's Pilot's Associate pioneered such task models in two different formats: a plan-goal modeling technique [5] and a Task Network representation based, ultimately, on PERT chart notations used in business planning [6].

These modeling techniques share several critical attributes, as illustrated in Figure 3. First, they are organized via hierarchical decomposition—meaning that beneath each task or goal the next lower layer represents alternate methods of achieving that goal, down to some bottom layer of executable, primitive actions. Models have both breadth and depth. Their breadth is the range of task domain which they cover. A task model for interactions with a weapon system is "narrower" than a model which covers all flight operations. Their depth is a measure of the degree of decomposition or "granularity" on the lowest level of actions represented—thus a model of flight operations which only represents major flight phases (e.g., take off, ingress, attack, etc.) is "coarser" than one which decomposes these actions still further.

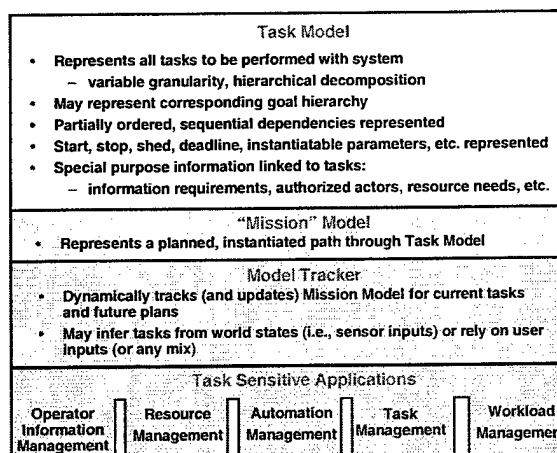


Figure 3. The various uses and instantiations of task models in associate systems.

Task models have both static and dynamic variations. In their static variation, they list all possible tasks that can be performed in this human-machine system (to some level of depth). From among this static set of possible tasks, certain tasks can be flagged and combined a priori as the expected states for some portion of the future (e.g., the mission plan). Static mission models may then be "tracked" or updated dy-

namically during operation to represent the current, unfolding set of tasks the human-machine system is actually engaged in—both indicating when various tasks in the mission plan become active and/or when the human operator has chosen to do perform some task which was not explicitly planned for this mission (e.g., react to threats).

The tasks represented in the model are (or should be) drawn from the way operators think about tasks, goals, etc. in their domain. They may be drawn from training materials or operator interviews. In any event, the resulting model should be easily readable by a trained operator in the domain. But tasks in the model must be interpretable by all automation systems which will use them (something like a football team's playbook—each player knows what he is supposed to do when a given play is activated and coordination is an emergent function stemming from their all sharing the same playbook). Thus, by 'calling a play' (that is, declaring that a certain task is to be accomplished), the operator can task automation subsystems to behave appropriately for the performance of that task.

In the creation of our tasking interface, we have extended the operator's ability to 'call plays' by providing them the ability to interact directly with the task model, activating tasks at various levels of decomposition. This capability is provided via the *Playbook GUI* described in the next section below. We have also provided a planning system which is capable of understanding the operator's commands and either evaluating them for performability or, when they are provided at a level higher than is executable by automation, of developing an executable plan which obeys, yet fleshes out, the operator's instructions. This *Mission Analysis Component* is described in the following subsection.

### 3.2 Playbook Graphical User Interface

The human operator must have a method of inspecting and interacting with the task model, both to understand the possible actions which could be taken to achieve known goals and, more importantly, to declare those tasks, goals, partial plans and constraints s/he wishes the system to pursue. This interface must provide the operator with a method of "calling plays" as described above. Through this interface the operator (e.g., pilot) will graphically construct a full or partial plan for the mission specifying the tasks (or "plays") to be performed and goals to be accomplished. Some requirements for the Playbook GUI we are constructing include: (1) the set of "plays" (e.g., maneuvers, procedures, etc.) represented will be those that any well-trained operator should know (thus making it intuitive and easy to learn and use), (2) the general play 'templates' in the playbook can be composed and instantiated to create any specific mission plan, and (3) The operator may select plays to be used at various levels in the hierarchical decomposition of the mission plan, leaving the remainder to be selected and composed by the Mission Analysis Component (see below), either requiring or prohibiting the use of specific plays. This makes true mixed initiative planning a possibility and will make the tasking of a UAV much like providing instructions to a human wingman.

A hypothetical example of a Playbook GUI is presented in Figure 4. While we are only beginning the development of this tool, some factors are already clear. First, the underlying links to a task model both permit and require a wide variety

of interfaces. The specific attributes of the GUI will be driven by the uses to which it will be put. As a simple example, a pre-mission planning tool will require much more flexibility and precision in visualizing and interacting with the emerging plan, while an in-flight tasking tool will be constrained to use something as simplified as a highly-attenuated menu of only those tasking options which are relevant at the current moment. Another factor which is becoming obvious in our initial development activities is that, while a direct presentation of the task model (as is illustrated in Figure 4) generally provides the most detailed and precise interaction with the emerging plan, it is neither the most familiar nor the most efficient presentation for many pilot planning tasks. Interaction with the underlying model via a map-based presentation and a simple timeline view are both being considered to address this problem.

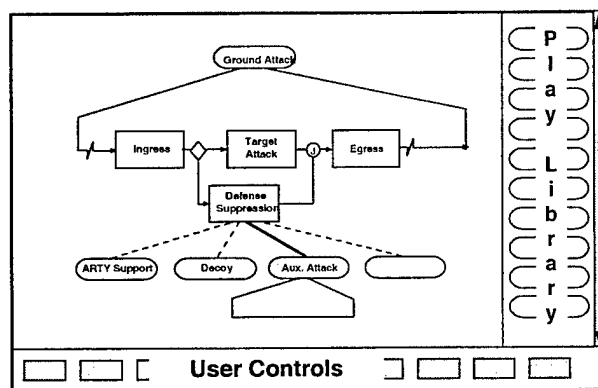


Figure 4. One possible instantiation of a playbook GUI.

### 3.3 Mission Analysis Component

The Mission Analysis Component (MAC) integrates projective planning technology with a human tasking mechanism. MAC operates over full or partial mission plans provided via the playbook GUI, performing two sub-functions: (1) analyzing the operator's plan for feasibility and goal achievement by means of verifying constraints and (2) automatically completing partial mission plans (or suggesting candidate completions) in keeping with the requirements and prohibitions imposed by the pilot. The hierarchical, typed representation of plays in the playbook simplifies choices for plan completion by limiting the types of plays which are useful at each level. Plays contain information about their expected and desired effects. This information is used by projection algorithms in the MAC to analyze the plan for correctness (i.e., will it achieve its stated goals if executed successfully?). Constraint propagation techniques are used to coordinate the individual plays chosen by the pilot or the system into coherent mission plans (e.g., once a target is stipulated for one phase of the plan, it is propagated to the other phases automatically). The MAC module we are developing draws on work in AI planning, but must be part of an approach bridging the traditional gap between analysis and execution.

Analytic capabilities developed in previous AI planners have used simpler, more abstract task representations and have made substantial assumptions about correct execution. Reactive planning and execution systems (such as those used in

robots) are essentially high level programming languages used to coordinate the behaviors and states of sensors, effectors and to handle contingencies—but without support for analysis of correctness. Honeywell is concurrently at work on an integrative architecture for projective planning, reactive planning, and control actuation, called CIRCA [7] which bridges this gap by synthesizing provably correct reaction programs in accordance with known goals. To date, however, little thought has been given to how an operator will provide those high-level goals. Our work fills that gap.

### 3.4 Integration and Operation

At the bottom layer of our architecture, advanced control algorithms provide for actual moment-to-moment vehicle control. The control algorithms provide several levels of functionality. The highest level is the ability to fly specific flight segments (e.g. close or loose formation, "pop-up" for weapon release, rendezvous). At a lower level are guidance functions like waypoint steering and terrain following. Finally at the lowest level are the attitude and rate stabilization control functions. The resulting "plan" created jointly by the human operator using the Playbook GUI and by the MAC's reviewing or fleshing out the human's instructions, along with reactive adaptations provided by the event handling component, gives these control functions the instructions they need to know which behaviors to execute. The result is a seamless ability for the operator to task and control the automation functions in a wide variety of ways depending on the human's available time and degree of trust.

## 4. A TASKING INTERFACE FOR UAVs

We have recently begun work on a proof-of-concept demonstration of this tasking interface architecture. We have chosen to work in the domain of Unmanned Air Vehicles (UAVs) both because this domain is of interest to Honeywell and its customers and because the tasking of UAVs by human operators already engaged in highly demanding activities (e.g., aircraft or helicopter pilots) is a good example of the situation depicted in Figure 1 above. Current and emerging UAV interfaces either require operators to remotely control the aircraft via a dedicated cockpit mockup, or they rely on very high level behaviors (e.g., Close Air Patrol circuits or waypoint-designated routes) which can be commanded but not modified. The first approach provides a high degree of predictability and adaptiveness, but only at the cost of very high operator workload; the second approach minimizes operator workload and provides highly predictable behavior, but only at the cost of adaptiveness. Neither of these approaches is sufficient for placing one or more UAVs at the disposal of an operator who is concurrently engaged in the piloting of his own aircraft. To make coordinated operations between a human pilot and UAV(s) feasible demands increases in adaptiveness without substantial increases in either unpredictability or pilot workload.

Building on prior control algorithms and simulation work supporting a scenario of one piloted F-16 with two unmanned F-16 "wingmen", we have begun developing a tasking interface to enable a human pilot to lay out a mission plan for the UAV's. This interface will support the stipulation of goals, partial plans, full plans and constraints for each of the UAVs either separately or in conjunction. We have begun our work

by concentrating on a ground-based tasking interface due to its lighter demands on pilot, simulation and interface design. However, we believe that, with suitable modifications to the GUI, this approach will be suited to in-flight tasking as well.

To date, we have used a variation on the PERT chart-based task network representation as pioneered by McDonnell-Douglas. A portion of this representation for the high-level task of "ground attack" is presented in Figure 4. While definition of the Playbook GUI is proceeding at this time, we will step through a representative example of interaction between the human operator, the Playbook GUI and the Mission Analysis component below.

The human "leader" of the pilot + UAVs team (presumably the pilot himself) would interact with the tasking interface to, first, declare that the "mission task" for the day was "Ground Attack." Having declared only that much to a team of trained human pilots, the team would have a very good general picture of the mission they would be flying; similarly, our interface (via the MAC) knows what a typical ground attack plan consists of. But just as a human leader instructing a flight team could not leave the instructions at that, so the human "tasker" is required to provide a bit more information to instantiate and bind the high level task. In this case, the tasker *must* provide at least the specific target of the ground attack. S/he could provide substantially more detail (such as take off time, route, munitions, roles for the wingman, etc.) but s/he could also hand the task off to intelligent team members at this point and let them work out the best plan they can come up with. The tasker can do this as well, using our interface to hand the task to the MAC with only this information. For our example, we will assume that the tasker wishes to provide more plan specifications.

Both the tasker and the interface know that any Ground Attack plan must consist of Ingress, Target Attack and Egress subtasks, in that order. It may also include a Defense Suppression task which would run in parallel with Target Attack. These relationships are depicted in the task network in Figure 4: conditional branches are indicated by diamonds, sequential relationships are depicted left to right and parallel tasks are depicted next to each other vertically with a round "join" node showing that both parallel tasks must be completed before the next task can begin. Figure 4 also shows the tasker selecting among alternative methods of performing the "Defense Suppression" task.

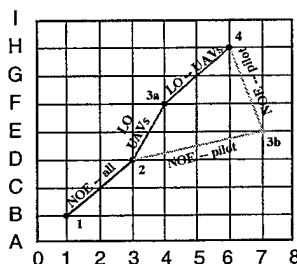


Figure 5. Hypothetical route plan.

Assume that the tasker wishes to provide detailed instructions about how the Ingress task is to be performed. His instructions are presented graphically in Figure 5. The tasker wishes the whole team to fly Nap of the Earth (NOE) from waypoint 1 to 2 and then to split, with the two UAVs flying a Low Observ-

able (LO) route to waypoint 3a and on to 4 (perhaps serving as a decoy), while the pilot will fly NOE to waypoints 3b and on to rejoin at 4.



In order to task the UAVs to perform in this fashion, the leader must begin by expanding the Ingress task in the plan developed in Figure 4 above. Upon doing so, he would receive the “generic” Ingress task representation shown in Figure 6.

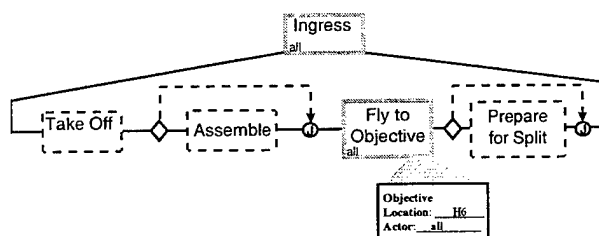


Figure 6. Expansion of Ingress Task.

It is important to note that this is not a default method of doing “Ingress” so much as it is a generic, uninstantiated method—corresponding loosely to what a human operator knows about how Ingress can or should be done in general. That is, the trained pilot knows that in order to accomplish Ingress, they will need to all Take Off, will probably need to Assemble, will certainly need to Fly to Objective and then Prepare for Split (assuming they assembled in the first place).

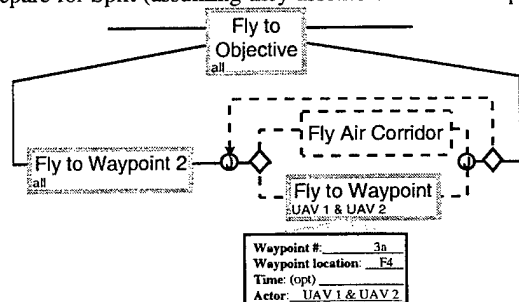


Figure 7. Expansion of Fly to Objective for second waypoint, UAVs only.

For our example, we’ll assume that the leader doesn’t wish to place constraints on how the Take Off and Assemble tasks are to be performed (that is, he will leave the planning of these tasks up to the MAC), but that he does wish to mandate that the “Fly to Objective” task be performed in a specific way. We are using a dotted line convention in these figures to indicate no constraints imposed, by either human or MAC, on the conduct of this task and grey lines plus shading to indicate that the pilot has imposed constraints. Tasks are represented by boxes, and the actor(s) associated with the task are indicated in the lower left corner of the box. Figure 6 also illustrates a pop up window via which the tasker can input required information for the task.

If the pilot expands the Fly to Objective task to begin to input his route constraints, he first gets a “generic” method of performing the task—as illustrated in Figure 7. This diagram says that one can fly to an objective by doing one or more (note the optional loop) Fly to Waypoint or Fly Air Corridor tasks. In Figure 7, the pilot has chosen a Fly to Waypoint task and is entering required information to indicate that all actors will fly to waypoint 2 at location D3.

Since the MAC realizes that the performance of this Fly to Waypoint task does not yet accomplish the parent task’s goal of reaching the objective (that is, of being at H6), MAC in-

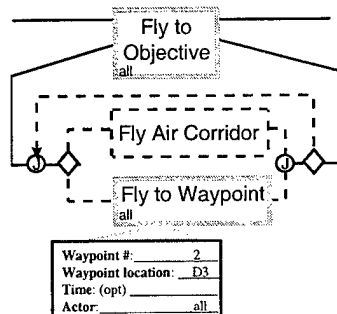


Figure 8. Expansion and stipulation of Fly to Objective Task.

structs the GUI to present another set of the generic options it knows are available to accomplish the goal. The developing task network is redrawn as in Figure 8. Here the first “Fly to Waypoint” task is included as a stipulated part of the plan, but the same set of choices is presented for the remaining flight segments, since the system knows that this is how “flying to an objective” can be accomplished. Again, the tasker could choose to leave the remaining specification to the MAC—in which case, MAC would develop a plan which incorporated the first flight or report that this was impossible. Instead, however, the tasker goes on to stipulate how the next segment is to be flown, indicating that the two UAVs are to fly to waypoint 3a by themselves.

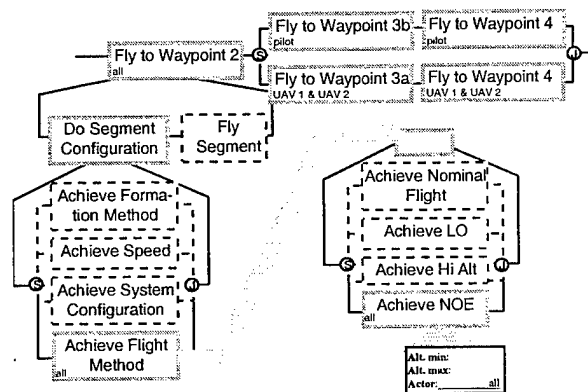


Figure 9. Expansion of Fly to Waypoint to flight parameters.

If the tasker continues to stipulate the set of waypoints indicated in the hypothetical route plan in Figure 5 above, the resulting task network would look like Figure 9, with separate branches for the pilot and the two UAVs for waypoints 3 and 4. Figure 9 also illustrates the further expansion of the Fly to Waypoint tasks to illustrate how the tasker can impose constraints on low level details about how the flying is to be done. By decomposing the “Fly to Waypoint” task down still further, the tasker can access attributes of the flying task: flight formation, system configuration, flight method, etc. Under each of these, there is a series of “Achieve” and “Fly” tasks which correspond to various options about how flight

may be performed. We have expanded the "Achieve Flight Method" branch to illustrate the stipulation of NOE flight for all actors for the first flight segment. The remaining segments could be stipulated similarly. Note, though, that the tasker has made no constraints on the remaining flight parameters, leaving MAC free to plan these as needed to accomplish higher level mission tasks or obey other imposed constraints. Note too, that the flight "behaviors" depicted at the lowest level in Figure 9 are now at the highest level that the control algorithms for UAVs are currently capable of executing. Thus, we have reached the level at which model development can reasonably end.

## 5. DIRECTIONS FOR FUTURE GROWTH

We are still in the design stages of our proof of concept tasking interface, but we are already identifying methods for improvement. First among these is the need to evaluate usability. We intend to allow pilots and engineers with military mission planning experience to review our prototype, but a thorough evaluation, ideally in comparison with traditional tasking techniques, would be more appropriate.

Although the focus of our initial research has been the development of the task model infrastructure and methods for human and computer sharing of it, experience indicates that we need several interface improvements. First, we must integrate the task model view (presented above) of the plan with alternate views including a map-based tool (to provide better orientation and a more familiar method of creating mission plans), and a timeline view to provide better visualization of the temporal layout of mission. Second, we need to enable rapid, simple interaction with the model at multiple levels—taskers will frequently wish to specify a general plan with one very detailed constraint (e.g., 'runway attack, but don't use rockeyes,' but with the current interface they can only reach that constraint by stepping through multiple layers of a detailed plan. Third, operators will wish to indicate that many tasks are to be done the same way (e.g., fly all waypoints after crossing the FEBA in NOE) but at present they must input this constraint separately for each task. We are now exploring the use of an object-hierarchy of tasks as a means of applying a constraint to multiple tasks within a class. Finally, we need a simple method of dictating negatives to the MAC—that is, stating that any method of accomplishing the task is acceptable *except* this one.

While we plan to address the above issues, further necessary developments are beyond our current scope: (1) Our current task network representation is weak in its coding of goals, and we believe that goals are a critical component of any tasking interaction [4]. Future work should explore representations which mix the sequential strengths of the task network with the goal-to-plan relationships of a plan-goal graph. (2) Tasking interfaces should not rely on a pre-defined set of task models. The operator should be able to create novel tasks and to store components of models which are useful. This indicates the need for a compositional tool and a library of stored models. (3) We believe that a "run-time" (e.g., in flight) version of the tasking interface is feasible and desirable. Such an interface would necessarily support a more narrow range of operator controls and modifications of the model. It should provide more rapid access to a tightly constrained set of alternate plans or modifications of high-level

parameters within existing plans. To facilitate transfer of training, however, it should maintain at least some of the look and feel of the ground-based tool.

## 6. CONCLUSIONS

Our approach to tasking interfaces is intended to build a bridge from current systems to true "associates". While pilots are rarely comfortable giving over authority to automation at all times and situations, they are willing to have it around for those times when it may be useful. Tasking interfaces are a method of allowing the pilot to remain fully in control, yet of enabling almost the full autonomy of an associate to plan and execute a high-level task whenever the pilot deems that that level of assistance is appropriate. The net result is a human-machine system which is almost as capable as an associate, and which reduces human workload almost as much, yet which leaves the human more in control than an associate does. Perhaps by requiring (and enabling) an associate to behave more like an intelligent subordinate, pilots will be more tolerant of their weaknesses and more willing to let them show their capabilities in tightly controlled settings. Through use, then, pilots may become more familiar with their strengths and, ultimately, more willing to tolerate them on a roughly equal footing in the cockpit.

## ACKNOWLEDGEMENTS

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## Electronic Crew Assistance for Tactical Flight Missions

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### 1 SUMMARY

Due to increasing demands put on crews of military aircraft, effective cockpit systems will be required in order to reduce workload and to improve crew performance. This paper presents an approach to crew assistance in tactical flight missions. The underlying tasks are tactical decision making, low-level flight planning and flight guidance. The Tactical Situation System as a knowledge-based crew assistant. It includes the capability of situation assessment and planning as well as a crew interface and a flight guidance display with sensor and synthetic vision components. The Tactical Situation System offers a promising solution to improve the situational awareness of the crew. A software prototype has been successfully tested and evaluated in a simulated environment as well as by flight trials.

### 2 INTRODUCTION

Human operators might be overtaxed due to the various tasks related to military air transport missions in hostile environments. Guiding the aircraft through adverse weather conditions in ground proximity puts further demands on crew performance. Most accidents can be at least partly attributed to human erroneous actions due to increasing crew workload. [3] Human-centered automation [1] offers a promising approach to the solution of the obvious problems of those design philosophies in flight deck automation just utilizing the available technology regardless of human needs.

The main scope of present programmes on on-board pilot assistance is the enhancement of the crew's situational awareness. Situational awareness is guaranteed if the pilot has all relevant information for the present flight situation at his disposal and is therefore able to cope with the posed tasks. In order to improve the situation assessment capabilities it must be ensured that the attention of the cockpit crew is continuously guided towards the objectively most urgent task of the situation and, if necessary, the workload reduced to a normal degree which can be handled by the crew. [3]

In order to meet the above design principles of the human-centered approach an appropriate crew assistant system has to incorporate the capabilities of situation assessment and planning in the field of tactical air-operations. The situation assessment has to be performed by the cockpit crew continuously during flight. In parallel the same assessment should be done by the functions of the machine part of the man-machine system.

Additionally, the visual perception aspects of human performance have to be considered. Enhanced and synthetic vision systems are today's solution in order to improve the crew's situational awareness in the context of low-level flight guidance. While classical flight director systems avoid or at least decrease the involvement of the pilot, enhanced/synthetic vision systems keep the pilot active in the flight guidance loop. This is achieved by depicting information suitable for each human performance level [4] instead of just appealing to the skill-based level as required for aircraft stabilization and control. Thereby, the principles of the cognitive approach to flight deck automation can be met.

This paper describes the design and functions of the *Tactical Situation System* representing a military operations related assistant system extended by the addition of an *Enhanced Flight Guidance Display System* to assist the pilot in manual visually guided flight at low altitudes and in adverse weather conditions.

### 3 THE TACTICAL SITUATION SYSTEM

The Tactical Situation System is a software prototype system developed utilizing spin-off effects from the activities of the Crew Assistant Military Aircraft (CAMA) [7], Enhanced Vision System (EVS) [5] and Future Large Aircraft Night and Adverse Weather Vision (FLA-NSWS) [6]. Primarily the military operations related aspects of crew assistance are covered. The aim of the investigations is to create flexible system prototypes for cockpit avionics in order to elaborate user requirements and evaluate respective prototypes with operational personnel under human-machine-interaction considerations. Advanced mission management technologies are demonstrated in order to support the pre-development phase of future air transport/weapon systems.

#### 3.1 Approach to tactical flight crew assistance

While performing a tactical low-level flight mission, deviations from a preplanned trajectory might be induced by the crew while reacting to a suddenly changing mission scenario. Under adverse weather conditions this creates a high crew workload and a loss of situational awareness concerning the aircraft's position and attitude relative to the terrain and the desired flight trajectory. The suggested crew assistant system is the *Tactical Situation System* [5]. It yields the capability of taking workload off the crew by giving decision aids while keeping up the crew's situational awareness. This is achieved by the integration of the following functional capabilities:

- Situation interpretation and assessment through terrain and threat analysis,
- Planning through on-board mission management and optimal trajectory generation,
- Situation visualization through enhanced and synthetic vision.

The following section contains a closer view to the architecture and functions of the Tactical Situation System.

### 3.2 Functions of the Tactical Situation System

The Tactical Situation System is designed as an on-board cockpit system with interfaces to the crew via cockpit displays and controls, to the aircraft systems, and to ground stations via data link. Based on the current tactical scenario the Tactical Situation System performs a situation assessment resulting in a danger and threat analysis. The latter provides the input for the flight planning, by computing an optimal trajectory in terms of survival probability according to the crew-given mission constraints. The trajectory is visualized on various cockpit displays such as a synthetic vision primary flight display and an advanced tactical map navigation display. Additionally the planned flight path can be issued to an aircraft-hosted flight guidance system in order to generate flight director commands or perform automatic flight control. Respective flight guidance symbology is fused with a sensor image and the latter superimposed by the an enhanced vision overlay for display on a cockpit head-up/level equipment.

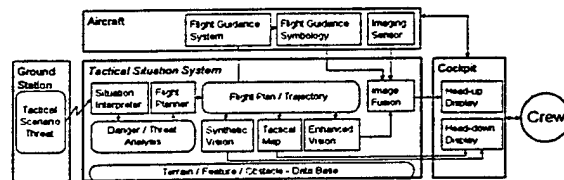


Figure 1: Modules and integration of Tactical Situation System

Figure 1 shows the modules of the Tactical Situation System and a suggested integration into existing aircraft avionics as used for the simulator trials described in section 4.1. The following subsections provide a closer insight into the functional details of the Tactical Situation System's core modules.

#### 3.2.1 The interactive tactical situation map display

The Tactical Situation Display provides the primary crew interface to the Tactical Situation System. Basically, it is an interactive electronic moving map display for navigational and operational purposes.

The aim of the interface is the improvement of the pilot's situational awareness by depicting situation relevant data. The actual information needed for task performance is highly influenced by the task itself. Obviously, the map information required for IFR flight is completely different to the information in the context of tactical navigation. Typically, the differences are more subtle. The Tactical Situation Display is primarily designed in order to cope with the advancing knowledge on human information processing. Therefore, it allows the composition of the display contents from a vector oriented database. The display utilizes digital terrain elevation data (DTED) and digital feature analysis data (DFAD) [10] in order to create a topographical map in any required scale and orientation. The various feature classes can be displayed selectively providing a very efficient decluttering of the screen contents. Radio navigation symbology can be added by visualizing Jeppesen Navigation Data. Military operations related aspects are covered by the

incorporation of tactical symbols. Furthermore, the interpreted tactical situation is dynamically depicted utilizing a three-dimensional threat coverage diagram. The threat map display can be activated for the different above ground levels or be slaved to the aircraft's present altitude. The mission plan and an optimized ground track of the low-altitude flight plan is indicated as in Figure 4.

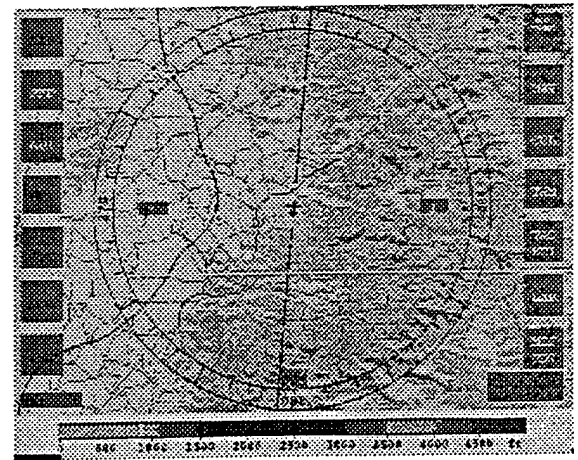


Figure 2: Tactical Situation Display

Figure 2 tries to give a general impression of the appearance of the Tactical Situation Display. It shows the display depicting the feature data and the ground elevation map in a 1:250,000 north-up representation. The system is designed as a head-down display.

The second main aspect of the Tactical Situation Display is on the side of control. It provides an interface to the

- Low-altitude flight planner. It allows the pilot to enter/edit waypoints interactively by marking them on the map;
- Tactical situation assessment by supporting the manipulation of tactical elements.

The control is done by use of a cockpit trackball for the analogue inputs and pushbuttons/touchscreen for the discrete inputs.

This concept fuses the functionalities of the navigation display with interactive elements derived from a flight management system control and display unit by creating a bidirectional interface. The integrated function is supposed to be situated on a primary flight display. Thereby, the unnatural separation of flight plan manipulation and depiction in current cockpits can be resolved.

The following two subsections describe the background modules of the Tactical Situation System which are controlled by the Tactical Situation Display and provide the actual assistance functions in terms of situation assessment and planning.

#### 3.2.2 The tactical situation interpretation

The Tactical Situation Interpreter is a knowledge-based module in the context of the situation assessment. Its main contribution is the computation of a *threat map* which gives a penalty value distribution over the considered operation area.

Hostile or threatening tactical elements are passed to the Tactical Situation System via a data link connection or can be entered into the system through the Tactical Situation Display. The tactical elements themselves provide little information to the crew in terms of decision aids. The tactical situation interpretation now assesses the tactical elements in

the context of knowledge about the surrounding world, the threat's characteristics and the ownship's capabilities and situation.

The calculations are based upon digital terrain elevation data [10] and the threat's models. Threats such as surface-to-air missiles (SAM) or radar sites are described by a set of typical parameters such as maximum range, operability, efficiency along range and respective models for threat area overlapping. Aeronautical constraints, restrictions, and tactical considerations can be incorporated as well.

Due to the characteristics of the threat's radar systems and respective radar shadows resulting from the terrain structure, the altitude above ground up to which an aircraft is not detectable by the hostile radar beams can be derived from the digital terrain elevation database (DTED). [8]

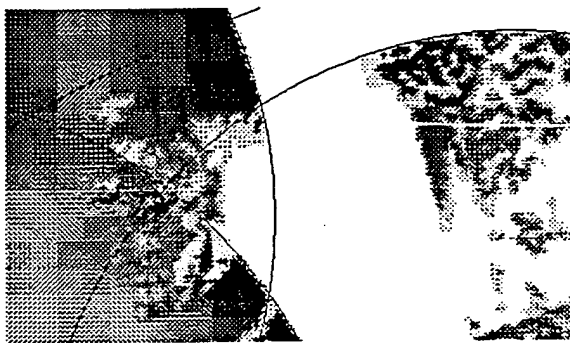


Figure 3: Threat map with SAMs' range circles

Figure 3 depicts a typical result of a threat map calculation. The result of the tactical situation assessment provides a powerful decision aid and a strong enhancement of situational awareness. The crew is enabled to identify the threat-free corridor in middle of the selected scene.

### 3.2.3 The Low-altitude Flight Planner

The Tactical Situation System allows the planning of a low-level flight mission interactively by use of the Tactical Situation Display (as shown in Figure 4). Relevant mission plan information such as heading, distance, timing are updated and displayed on-line. The waypoint planning is done with respect to the given mission constraints.

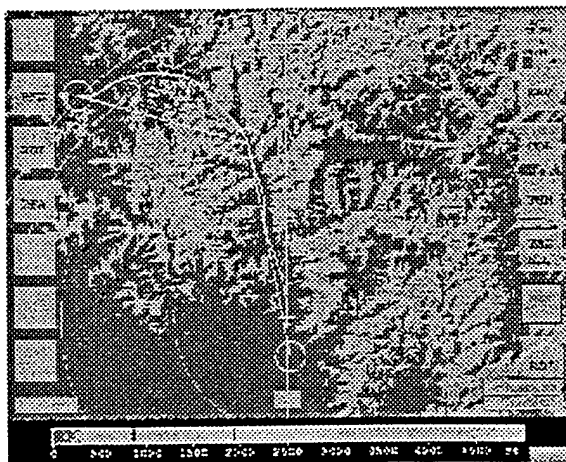


Figure 4: Mission planning with the tactical map

The aim of the Low-altitude Flight Planner is the calculation of a three-dimensional route between the mission-given

waypoints with a maximum probability of survival in a hostile environment. This is achieved by avoiding threatened areas if possible, minimizing the exposure to unknown threats and keeping clear of the terrain. Therefore, the mission constraints, the tactical elements and the resulting threat map, the terrain elevation data and the aircraft performance data are taken into consideration. The output of the planner is a detailed trajectory and a waypoint/flightleg-oriented representation. Figure 5 shows the architecture concept of the planner.

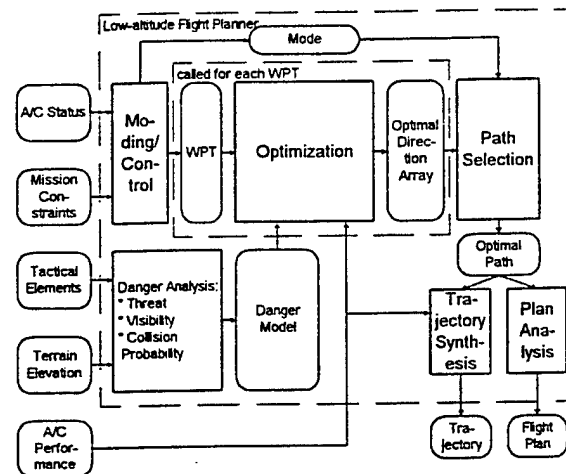


Figure 5: Low-altitude Flight Planner architecture

The system consists of three main functional submodules:

1. The *danger analysis* incorporates the threat map calculation as described in subsection 3.2.2. Additionally, the visibility at each point is calculated without assuming any particular threats. The algorithm issues lower danger values on the side of valleys than in the center. This behaviour reflects pilot's low-level flying preferences. Finally, the danger analysis utilizes the calculation of a ground collision probability, which is particularly high in rough terrain. This feature leads to generally higher flight altitudes in the absence of threats. An overall penalty value is calculated for each terrain grid point and stored as a danger model in an array.
2. The *moding/control* checks the flight status and assembles the target point and the planning area for the *optimization* according to the mission constraints. The numerical optimization is based on dynamic programming [2]. The optimization provides an array of optimal directions to the target point. As long as a replanning does not imply a new target point another optimization run is not required. This means that the algorithm offers an optimal path from each point in the planning area to the desired target point. This peculiarity of the algorithm provides a most powerful assistant function of the low-altitude planner: the *rapid in-flight replanning capability*. This function allows the generation of a new optimal trajectory starting at the aircraft's present position within a single second. In the case of intended or involuntary deviation from the preplanned track, a recovery trajectory can be issued taking the terrain, tactical situation and mission goals into consideration. The function can be activated intentionally by the crew, by a ground proximity system alert or any other appropriate crew assistance function.
3. The *path selection* depends on the current planning mode (initial planning or replanning). It constructs a terrain grid based flight path from a given start point or the

present aircraft position to the target point. The *output assembly* functions *trajectory synthesis* and *plan analysis* form the Low-altitude Flight Planner output.

- In order to be monitored by a pilot model based assistant system, such as CAMA [7][8], the representation of the detailed trajectory has to be reduced to a waypoint based low altitude flight plan, which represents the general considerations to be followed in the human planning of low level missions i.e. threat avoidance, terrain masking, timing etc. The reduction is done through a low pass filtering operation of the optimal trajectory.
- Additionally, the low-level flight plan is given by a detailed trajectory representation. Thereby, an assisting function on the skill-based human performance level can be provided. During normal operation the pilot selects the trajectory to fly by the consideration of relevant influences. The execution can be monitored by the crew assistant. In situations of increased workload it is possible that the pilot is no longer able to select a safe and efficient flight path. In this case the display of the automatically generated trajectory is a helpful tool.

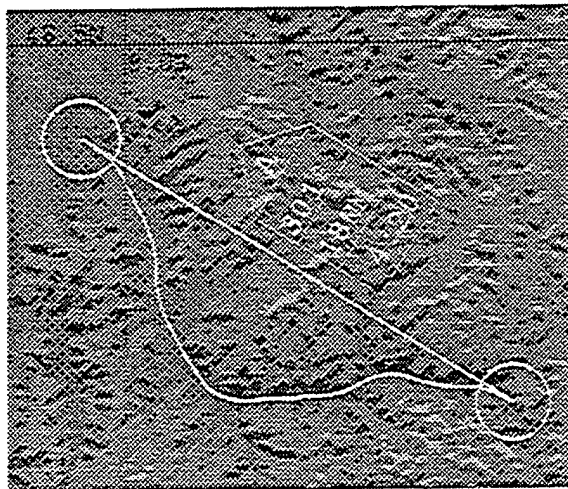


Figure 6: Trajectory and mission plan on elevation map

Figure 6 shows a typical planning result between two waypoints considering only the terrain elevation. The result is an optimal trajectory minimizing the cost function of weighted terrain elevation data and local threat values integrated over the complete flight path.

Obviously there has to be some function which provides crew assistance on following the optimal trajectory in terms of primary flight guidance. The following subsection gives an overview of the flight guidance incorporated in the Tactical Situation System.

### 3.2.4 The Enhanced Flight Guidance Display

Several scientific research studies [9] start from the assumption that the pilot's information gathering from the out-the-window view is critical for flight guidance in low-level flight and landing tasks. Flying under restricted visual conditions requires additional technical means to assist the pilot in performing the task. Classical flight guidance systems for instrument flight, such as flight director display or ILS indicator, give only very reduced information gathered by simple sensors from the real-world situation. Therefore, the pilot's situational awareness might be fairly low and the pilot still has to learn adapted flying skills instead of just utilizing

his natural and extremely powerful skills of flying in a three-dimensional visual world.

The Enhanced Flight Guidance Display is a promising approach to the solution of the problems of poor visibility low-level flight. It comprises an imaging sensor (e.g. FLIR, mmWR, LL-TV) and the superimposition of the sensor image with a computer-generated three-dimensional cockpit view. The incorporation of sensory data is essential for the benefit of the system. Due to incomplete or incorrect databases, the pilot cannot only rely on the synthetic image components. Inaccuracies of the navigation system yield another basic problem for just synthetic vision systems.

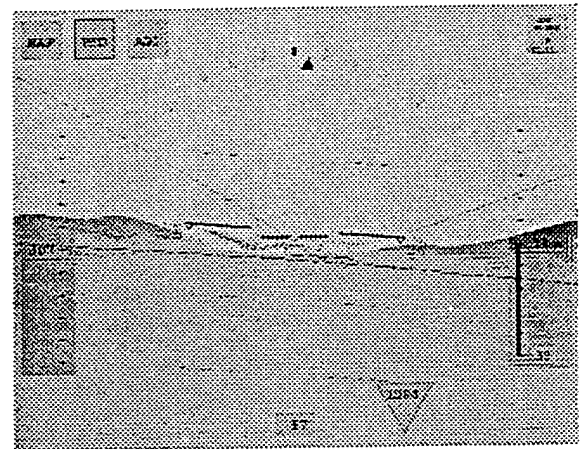


Figure 7: Synthetic symbology of Enhanced Flight Guidance Display

Thus, the Enhanced Flight Guidance Display is not a visual simulation. It does not try to produce a most realistic representation of the out-the-window view as used in visual systems of training flight simulators but is instead a display carrying situation and task relevant information.

Therefore, the Enhanced Flight Guidance Display consists out of the following visual components:

- The *non-conformal flight guidance overlay* is a standard head-up display symbology with speed, altitude (MSL, AGL), heading, vertical velocity readouts and a bank and sideslip indicator.
- The *conformal flight guidance symbology* incorporates an attitude display and artificial horizon. The flight guidance tunnel visualizes the three-dimensional flight trajectory. A velocity vector and flight path predictor depict dynamic aircraft movement information. [9] The predictor symbol (not used in flight trials) consists of three U-shaped brackets (for the 1, 2 and 3 second prediction) in order to fit into the flight guidance tunnel. The symbology is denoted as *tunnel dock*.
- The *conformal terrain contour symbology* is a perspective depiction of the digital terrain elevation database. Air traffic obstacles exceeding a minimum height taken from the digital feature analysis database are shown as well as airfields.
- The *sensor image* is added to the synthetic parts of the display in order to cope with incomplete databases.

Figure 7 tries to depict the synthetic parts of the display. The format shown is typical for a head-down application, because of the coloured terrain surface. The colouring is switchable between:

- an absolute elevation coding colour key as used in the map display and



- a collision warning colour code, which assigns red colour to the terrain higher than the ownship altitude.

The same colour codes can be independently assigned to a perpendicular east/north-fixed terrain grid. Using only the terrain grid without the surface colouring produces a more head-up display type symbology which is applicable in combination with the sensor image (see Figure 8).

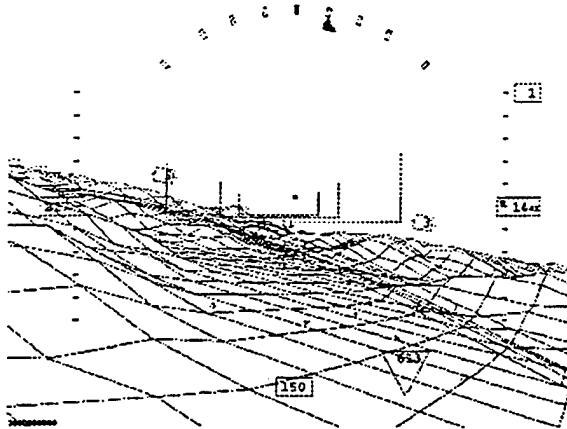


Figure 8: Flight guidance symbology for sensor image combination

The software prototype of the Enhanced Flight Guidance Display is designed in order to allow rapid changes of formats and functions to easily meet user and design requirements.

#### 4 EVALUATION CONCEPTS

In order to evaluate the approach to crew assistance, particularly the Tactical Situation System, software prototypes are implemented and integrated in appropriate test environments. Tests have been carried out with respect to technical feasibility, human-machine-interaction considerations, and real-world conditions. Therefore, the Tactical Situation System and various subsystems have continuously undergone critical evaluation procedures which are described in the following sections.

##### 4.1 Simulator trials

The *Tactical Situation System* was designed and prototyped in a generic cockpit simulator [5] at ESG and then integrated and evaluated in the Daimler-Benz Aerospace DASA Airbus development flight simulator for Future Large Aircraft at Hamburg. The main objective of the experiment was to investigate whether the crew performing a tactical flight mission under adverse weather conditions could be effectively assisted by the prototype system in terms of situational awareness improvement.

##### 4.1.1 Apparatus

The experimental system was a full scale three-seat fixed-base flight simulator equipped with a collimated wide FOV visual simulation system. The cockpit hosted two 10 inch high resolution CRT displays for each crew member and a collimated head-up display for the pilot flying. Flight control was provided by Airbus cockpit controls including sidestick control. The crew's control actions were passed to an Airbus flight control system. Flight director signals were provided by a low-level flight guidance system.

##### 4.1.2 Subjects and scenario

The subjects were seven German Air Force pilots: four of them tactical transport instructor pilots, two test pilots with fighter experience, and one civil transport pilot. Each of them had to perform a tactical low-level transport mission of about 45 minutes. The mission contained portions of transit and tactical flight. Low-level flight was performed at 250 ft AGL utilizing terrain masking in mountain valleys. Additional features of the mission were a tactical drop procedure, an intended deviation from the preplanned track with an unguided recovery, and the performance of an unguided go-around pattern at the destination airfield. The whole mission had to be performed under night and low visibility (400 meters) visual conditions.

##### 4.1.3 Evaluation results

One of the main objectives of the described experiment was the knowledge elicitation for future developments in the field of cockpit systems design. Therefore, a continuous assessment of the prototypes was performed during the simulated flight by applying the method of observation during task performance. Additionally, debriefings with questionnaires were conducted. The observations showed that the preferred configuration of the Tactical Display was a height-colour-coded terrain relief with a collision-warning overlay. This supported terrain avoidance and the low-level flight guidance task extremely well. Crew coordination aspects were promoted significantly by the integrated display concept. Concerning the head-up display, a strong enhancement could be achieved by adding a (simulated) FLIR image. The ability of ego-motion estimation in the Synthetic Vision alone was regarded as insufficient. Overall, a total of seven one-hour low-level flight missions were successfully conducted under visual conditions prohibiting unaided terrain masking. An unguided go-around manoeuvre was performed successfully three times. Two touch-and-go procedures were conducted utilizing the Synthetic Vision navigation capabilities.

#### 4.2 Flight trials

In order to evaluate the Tactical Situation System under real world conditions flight trials were conducted recently.

##### 4.2.1 Apparatus

The experimental platform was a two turbo-propeller engine Dornier 128 aircraft provided by the Technical University of Braunschweig. It was equipped with a hybrid high precision differential GPS / laser INS navigation system.

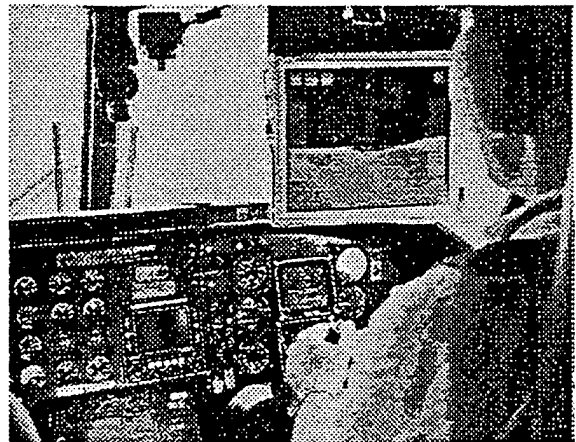


Figure 9: Experimental cockpit display

The experimental cockpit was equipped with a head-up mounted 13 inch high resolution LCD flat panel display. Figure 9 shows the experimental cockpit display obscuring the test pilot's out-the-window view. A Silicon Graphics Indigo2 High Impact graphics workstation hosting the experimental software was mounted in a shock-absorbing rack.

#### 4.2.2 Subjects and scenario

The subjects were two scientific test pilots, one working as safety pilot and the other as experimental pilot. A total of six low-level flights were conducted at altitudes of approximately 500 ft AGL. The main task was to navigate in terrain proximity and perform terrain masking in mountain valleys. Point to point navigation utilizing the visual identification of waypoints was to be conducted. On-board planning and in-flight replanning tasks were added. The actual mission contents were designed with respect to familiarization and training considerations and became increasingly complicated.

For safety reasons the flights were performed under VMC. As they were meant to be under adverse weather conditions, the outside view of the experimental pilot was obscured.

#### 4.2.3 Evaluation results

Firstly, the flight trials were evaluated under the aspects of technical operability of the assistance functions under real-world conditions. It showed that an on-board full mission preparation and planning could be conducted including autonomous trajectory generation. High precision visual navigation tasks with waypoint identification were successfully performed. The crew was enabled to cope with an in-flight change of the mission order by conducting an automatic full replanning. Experimentally induced trajectory deviations could be recovered by the crew by use of the rapid in-flight replanning capability of the Tactical Situation System. Situational Awareness was guaranteed by the terrain visualization. Generally an excellent overall pilot acceptance could be gained for the functions and formats.

A second major concern of the evaluation was the assessment of the pilot's situational awareness with respect to certain situational elements. To achieve this, questionnaires were completed by the pilot after the flight missions. Generally, it can be stated that the situational awareness for aircraft attitude, altitude and speed was regarded as good. Concerning the ownship attitude or proximity with respect to obstacles and terrain, the synthetic vision format could be improved. The depiction of the tasks and mission progress was regarded as very helpful.

In future additional support of the navigation system's altitude channel by the radar altimeter and the terrain elevation model would be advisory for further experimental activities.

## 5 CONCLUSIONS

The aim of the presented research and development activities is to provide advanced cockpit avionics systems improving the crew's situational awareness with respect to a safe and successful mission completion. This is done by use of technical means such as knowledge-based on-board systems in the context of human-centered cockpit automation. The Tactical Situation System yields a promising approach to assistance in tactical flight missions containing planning and decision-making tasks as well as low-level flight guidance. The military operations related subsystems are the Tactical Situation Interpreter, the Low-altitude Flight Planner, and the Tactical Situation Display. The system is enlarged by the

Enhanced Flight Guidance Display which offers visual flight guidance information to the crew for poor visibility low-level flight operations. Thereby, crew assistance can be provided on each human performance level including highly cognitive planning tasks as well as sensorimotoric flight control tasks. A major aspect of the prototype development is the integration of the different modules in order to achieve an efficient assistant system.

In order to evaluate the system under technical and human-machine-interaction aspects, software prototypes are being developed and integrated in a flight simulation environment. A particularly successful flight trial for the integrated assistant system has been completed recently. The results show that this approach to visual flight guidance assistance is extremely powerful and yields a high potential for further developments in the field of human-centered cockpit design.

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# DEVELOPMENT OF A TACTICAL ADVISER FOR AIR COMBAT

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## SUMMARY

The JOUST facility at DERA Farnborough is a work-station based man-in-the-loop simulator, capable of allowing many pilots to engage in simulated air combat. It was created in order to perform high quality operational analysis of air combat issues using human pilots. The requirement was partly due to the fact that existing computer only models were insufficiently capable of representing all the tactics and pilot abilities used in a modern air battle.

In the past six years more than fifty trials have been conducted using front-line aircrew, tactics experts and DERA scientists. As a result the JOUST team have considerable experience in modern air combat tactics and software modelling. The JOUST software consists of a number of high fidelity models representing systems such as the aircraft, missiles, radar and electronic warfare, along with software for monitoring and controlling the simulation.

Three years ago work started on the development of an automated pilot for the JOUST system known as 'Joe'. Joe's tactics are written entirely in FORTRAN 77. This may be considered an unusual language to use by modern software engineers and artificial intelligent experts. However, the authors strongly believe that the major problems lie with quantifying tactics into hard unambiguous rules and that the implementation of these rules in software is a relatively trivial problem in comparison. The Joe system is an excellent environment for the development and testing of tactics software as all the cockpit displays are animated in exactly the same way as if a human pilot was flying. A pilot is able to shadow Joe's decisions throughout a combat and decide if he would make the same decisions based on the information presented. At his present state of development Joe is as good as the average pilot that flies on JOUST, with his strength being the accurate flying of his aircraft.

A natural development of this work was to develop Joe into a tactical adviser for a human pilot. A prototype system has been produced and utilises standard JOUST simulator station and software, Joe's tactics, and direct voice input and output so that the pilot can interact with the software. The major problems have been found to be in the quality of Joe's tactics and this obviously hinders the type of advice that can be given to the pilot. If in the fullness of time Joe becomes very adept at making tactical decisions, then we are faced with the philosophical question; do we actually need a pilot in the cockpit? Work is still continuing on improving this system, along with looking at other aspects of tactical decision aids

such as the use of fast fly-out missile models for predicting threat levels.

## 1 INTRODUCTION

The current aerial battlefield is a complex environment imposing a high workload on the pilot. Advances in sensors, communications and weapons systems will all confer a greater capability to future fighter aircraft, but unless properly managed will add to the pilot's workload. An additional consideration is the current trend in fighter aircraft design to move away from dual crew aircraft (e.g. F3 Tornado, F-4 Phantom) to single seat aircraft (e.g. EF 2000, F-22, SU-35). To provide some balance, there is a need to incorporate a high degree of computer automation in any future cockpit.

The aim of the work carried out by System Integration Department was to investigate the problems associated with a computerised tactical advisory system that could be used to assist pilots engaged in air combat. The ultimate goal was to develop a prototype tactical adviser (RITA - Real time Intelligent Tactical Adviser) for use within the JOUST simulation system and demonstrate that it can increase the combat effectiveness of a RAF fighter pilot of average ability.

The design of RITA drew on two existing areas of work. The first comprised of a number of functions built into the JOUST weapon system that were designed to reduce pilot workload, and the second was a prototype computer-controlled opponent for the JOUST system known as 'Joe'.

The primary technical issue was to decide exactly which aspects of an on-going combat a tactical adviser could be most useful. This was achieved partly by using the experience gained from the large number of air combat studies which had already been carried out using the JOUST simulation facility and also by conducting discussions and interviews with front-line aircrew. It was expected that the adviser would have to be tailored more to the needs of a relatively inexperienced pilot, rather than a seasoned fighter pilot. The aspirations people had for the tactical adviser also had to be tempered by what was practically possible within the timescales and current computational capacity. It was recognised from the outset that, for the foreseeable future, no computer is likely to have the tactical intuition of a well-trained fighter pilot.

## 2 JOUST SIMULATOR OVERVIEW

The JOUST system is a workstation based multi-player air combat simulator. It was developed by DERA to conduct operational analysis and has been in operation since October 1991. The systems that are simulated have been validated

against existing reference models and a wealth of knowledge has been built up within the research team. JOUST has proven to be extremely flexible and reliable in its six years of operation. During this period many simulated air combat trials have been undertaken, for various MoD, industry and overseas sponsors. The research team is made up of ten scientists and engineers and one RAF aircrew officer. In addition to support from other experts in DERA the facility has a close relationship with various parts of the RAF, RN and UK MoD, including Operational Research branches, the Air Warfare Centre the Tornado F3 Operational Evaluation Unit and front line aircrew. The role of the JOUST facility is to provide a diverse simulation environment capable of supporting aeronautical system trade-off studies, tactics development, human factors studies and training technology requirements studies, in order to improve the combat effectiveness of fixed wing fighter aircraft.

The architecture of the JOUST system allows for two opposing teams of multiple manned simulated aircraft, with the facility to introduce computer generated air and ground threats (see Figure 1). The cockpit stations can be of a medium fidelity desktop arrangement (see Figure 2) or high fidelity cockpit mock-up. Each cockpit station comprises of at least two Silicon Graphics computer workstations. One generates the out of cockpit display which includes a basic representation of ground, sky and weather, generic fast jet format head-up-display and all the aircraft, vehicles, missiles and countermeasures that would be visible to the pilot. The other runs the models which comprise the simulated aircraft, the interface to throttle, stick and switches and also generates the head down instrumentation, including a combined radar and IRST B scope, a tactical display, a RHWR display and a weapon status panel (see Figure 3).

The majority of the JOUST system is written in FORTRAN and the entire system consists of approximately 275,000 lines of code.

### 3 THE DEVELOPMENT OF JOE

As previously mentioned the JOUST facility was created to carry out operational analysis using men-in-the-loop. Historically this work had been done within the UK using purely digital models, that 'flew' the aircraft in the combat. There were two major problems with this approach:

- a. For a new aircraft concept it was hard to determine the best tactics to use, especially if the system under consideration had both good and bad points, for example an aircraft with superb energy agility but with a relatively small fuel load.
- b. Having determined the ideal tactics, it is very hard to get a computer to perform these tactics in a sensible and robust manner.

There is however still a need for digital simulations as man-in-the-loop simulations are generally more expensive and constrained by time in what they can achieve. Hence a few years ago the development of a new digital air combat model was started using a relatively novel approach.

Existing digital models such as ATEM in the UK and BRAWLER in the US are very large programs that run on a single computer in non-real time (either faster or slower), simulating all the players in a combat. The approach adopted here was to develop an automated pilot that could fly the existing JOUST simulator system of networked pilot stations in Beyond Visual Range (BVR) air combat. It was recognised from the outset that this was a very difficult task and it was very unlikely that the automated pilot would ever present a serious challenge to a good fighter pilot. Hence rather than choose a pretentious name for the automated pilot, he was simply given the name Joe, short for Joe Numbnuts.

The software architecture of a Joe station is almost identical to that of a manned station, with the only exception being that rather than call the routines that read the hardware, Joe's tactics logic is called instead. In order to fly his aircraft Joe has to manipulate the control stick in an identical manner to a human pilot, for instance banking and then pulling back on the stick in order to turn.

There are a number of advantages to this approach, the greatest being that it is an excellent environment to develop and judge tactics. In a conventional digital model the automated pilots behaviour is generally only judged by observation using some form of God's eye display. In the Joe approach all the pilot displays (radar, RHWR, tactical, HUD etc) animate in exactly the same way as if a pilot was flying. When implementing tactics the developer can 'shadow' fly the JOUST station, looking for all the cues that would lead him to make a tactical decision if he was actually flying the station. To judge Joe's behaviour the developer is able to see, via the head down displays, all the information that Joe is basing his decisions on. Very often a decision which looks odd when observed from a God's eye display, is perfectly reasonable when you see Joe's sensor displays.

Another major advantage of this approach is that it uses existing, well tested software models. This is obviously an advantage for financial reasons, but it is also a major advantage for validating the models. A man-in-the-loop simulator is a much more demanding environment when assessing the robustness of the models than a purely digital simulation. If a pilot perceives a deficiency or bug in the radar model for instance, such as the radar failing to lock when he expects it to, he will call attention to the fact. In a purely digital simulation a situation like this may easily be overlooked, as there is no pilot there to complain. As Joe's software models are used in exactly the same manner as they have been used in thousands of hours of man-in-the-loop flight simulation, it is reasonable to have confidence in them.

An advantage for a facility that already has manned simulators of this type, is that the simulation computers can be put to good use at times when they would normally be dormant, such as overnight and at weekends. Obviously if a research group only wanted to do digital simulations, this would be a very expensive approach because of the large number of computers it requires (at least one for each combatant).

Another disadvantage is that Joe is constrained to run in real time. The primary reason for this is the computing power

required but also if the models were run faster than real time it might highlight software bugs that are not critical in the manned version of the software when running at real time.

Joe's tactics consider the following aspects of BVR air combat:

- a. Situational awareness.
- b. Sensor management.
- c. Energy management.
- d. Judgement of danger level.
- e. Co-operative tactics.

Joe's tactics are written entirely in FORTRAN and although this may seem very 'quaint and out-dated' by modern software engineers and artificial intelligent experts, there are some very good reasons why FORTRAN is as good as any other approach. Firstly most of the so called Intelligent Knowledge Based Systems (IKBS) languages encountered by the authors have little or no intelligence. They generally break down into constructs similar to FORTRAN If.....then.....else statements, although this is not always apparent at first.

Although IKBS languages do offer advantages such as rule tracers, editors etc. the authors strongly believe that the major problems lie with quantifying tactics into hard unambiguous rules and that the implementation of these rules in software is a relatively trivial problem in comparison. For instance, take a relatively simple rule such as 'when in danger run away'. Danger has to be defined as a combination of range to a target, do I think the target can see me, do I think the target wants to engage me in a multi-bogey scenario, am I inside the targets weapon envelope etc. Run away has to be defined as what heading do I turn onto (for example a reciprocal heading or one towards friendly forces), how much 'g' do I pull during the turn, do I dive to gain speed in the short term or do I climb to the tropopause to gain speed in the long term. The rule has to be structured so that it is not called when the most appropriate action to reduce the danger is to try to shoot down the opponent. The rule has to be undertaken with a certain amount of decisiveness, but not too much otherwise it will inhibit a more appropriate rule from being carried out when the situation changes significantly. Sorting out all of the above problems can often take 80-90% of the time, with the coding and testing taking a mere 10-20%.

Other good practical reasons for using FORTRAN within the JOUST facility are :

- a. The staff are all current in FORTRAN
- b. The tactics software interface easily with the models, that are themselves written in FORTRAN
- c. There is good software support and the compilers are relatively bug free.

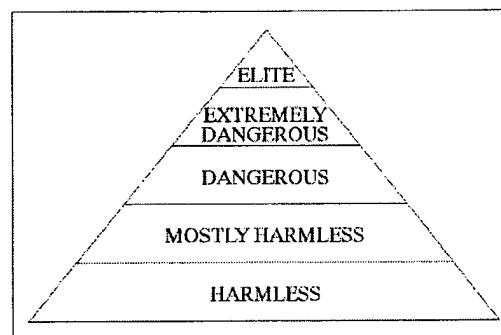
Joe's tactics currently consist of approximately 4,000 lines of FORTRAN code, not including comments and blanklines.

There are probably people reading this paper who disagree with the preceding comments and think this approach has very little going for it compared to more modern Artificial Intelligence techniques. However at the end of the day there is

only one way to judge the approach taken and that is how good is the artificial pilot in combat?

To judge Joe's combat performance the JOUST ranking system has to be first introduced (see Figure 4).

A typical JOUST trials pilot will be of Squadron Leader rank and come from an air defence background. During a week of training he will progress to the 'Dangerous' category. After



about two or three trials (approximately 100 hours of flying) 90% of pilots should progress to the 'Extremely Dangerous' category.

Figure 4 - JOUST ranking system.

Joe in a 1 v 1 scenario is at the top of the 'Extremely Dangerous' category and in a bigger scenario such as 4 v 4 he is towards the bottom of this category. The reason for the difference is that 4 v 4 is a more confusing, tactically challenging scenario than 1 v 1, which is dominated by aircraft/weapon performance. Considering Joe's strengths and weaknesses, his greatest strength is in energy management and accurate flying, which taken in isolation would put Joe well into the 'Elite' category.

#### 4 THE DEVELOPMENT OF RITA

A natural development of the work carried out on Joe was to try to develop Joe into some form of tactical adviser for a pilot. A prototype system was developed called RITA (Real-Time Intelligent Tactical Adviser) that used a standard manned JOUST station and software that incorporated a modified version of Joe's tactics (see Figure 5). Interaction with RITA is accomplished via Direct Voice Input (DVI) and Direct Voice Output (DVO). The DVI equipment was procured from the DERA Speech Research Unit based at Malvern and is called an AURIX. The AURIX has the advantage that it is speaker independent and has a very user friendly development environment, which makes it ideal for rapid prototyping. In practice the AURIX has achieved a recognition success rate in excess of 90% and has demonstrated that it will tolerate many different user accents.

The features currently incorporated into RITA are -

- a. Different stages of auto-pilot control.
- b. Sensor management.
- c. Targeting advice.
- d. Energy management advice.

e. Steering advice.

The major problem at the moment is in the quality of Joe's tactics and this obviously hinders the type of advice that can be given to the pilot. Remembering that Joe's strengths lie in the areas of accurate flying and energy management it is not surprising that the most useful RITA features are the different forms of auto-pilot control.

The first form of auto-pilot is a conventional heading/pitch auto-pilot but with the auto-pilot commands such as desired heading being input via the DVI system. The next form of auto-pilot flies combat manoeuvres such as a F-pol manoeuvre after missile launch. During the F-pol RITA will fly the aircraft to keep the target within a few degrees of the edge of the sensor coverage, whilst at the same time adjusting speed and height for tactical reasons. When the missile no longer requires sensor support RITA will inform the pilot via DVO that the F-pol manoeuvre is finished and then hand control of the aircraft back to the pilot. The last form of auto-pilot performs all the flying (engaging, f-poling, defensive flying, re-engaging etc.) leaving the pilot free to concentrate on the more complicated tactical aspects of the combat.

All the auto-pilot functions can be modified in terms of how much 'g' they pull, by the use of DVI commands. Combat manoeuvres can be customised via the DVI, such as in the F-pol manoeuvre the direction of the F-pol can be defined, overriding the direction suggested by RITA. When the auto-pilot performs all the flying the pilot has control over items such as which target is engaged.

An aircraft that effectively flies itself in combat has met with mixed responses from aircrew interviewed. Surprisingly, pilots are happier about the prospect than are the backseat navigators. This is probably because the navigators have more experience of getting thrown about when the aircraft performs unpredicted manoeuvres.

This all leads to an interesting conclusion. The current air defence fighter in the RAF is the two seat Tornado F3 and the next fighter will be the single seat Eurofighter. The work on tactical advisory systems was started because of a need to help the single seat pilot. The perceived view of a computerised adviser is to replace the navigator in the back by some form of 'R2D2'. However given the strengths of computers compared to the intelligence of man, if you really want to improve the combat effectiveness of a pilot in BVR air combat it is better to put 'R2D2' in the front seat carrying out the flying and have the human in the back seat planning the tactics and gathering situational awareness.

## 5 CONCLUSIONS

The approach to producing a digital pilot for air combat has proven very successful and Joe is continuing to be developed such that he can address a wide range of operational analysis issues. A new role for Joe is to be part of the research being carried out in the emerging field of combat Uninhabited Air Vehicles (UAVs).

The development of RITA has proven less successful. The major problem with this work is in the quality of Joe's tactics

compared to an average pilot and this obviously hinders the type of advice that can be given to a pilot. If the pilot feels he can not rely on Joe to make good decisions and has to continually monitor Joe's actions then this could actually increase his workload. If in the fullness of time Joe becomes very adept at making tactical decisions, then you are faced with the philosophical question; do we actually need a pilot in the cockpit?

At present it seems the best way to improve the combat effectiveness of a single seat pilot is to provide him aids to his own tactical decision making process, rather than to provide him with direct tactical advice which at best will be mediocre. An example of a current aid in the cockpit is the display of a missile launch success zone (LSZ). The LSZ tells the pilot if his opponent is within range and where the range is with respect to an 'edge of the envelope' or a 'heart of the envelope' shot. The LSZ does not tell the pilot when to shoot, that is a decision he makes by balancing the risk level to himself to how badly he wishes to shoot down his opponent. Other work (ref 1 & 2) has shown that pilots doubt the ability of any computer algorithm to correctly account for all the tactical factors they consider during combat. Further work should concentrate on developing new aids which will help the pilot in judging the relative merits of a particular course of action he selects.

An alternative method of improving the pilots effectiveness is to reduce his workload, so allowing him more time to devote to tactical thinking. Allowing RITA to fly the aircraft in combat manoeuvres is an example of this. However this example in particular is likely to meet with resistance from aircrew. In general the controls to all the systems should be de-coupled such that the pilot always issues high order commands and lets the systems work out the best way to achieve the results. Existing fly-by-wire aircraft already do this in that rather than use the control stick to move the elevator directly, the control stick passes a demand to the flight control computer which then moves the elevator, canards, flaps, slats etc. appropriately.

Work is continuing at Farnborough and the major challenge is coming up with good ideas that are practical to implement, will be useful to aircrew and will be accepted by aircrew.

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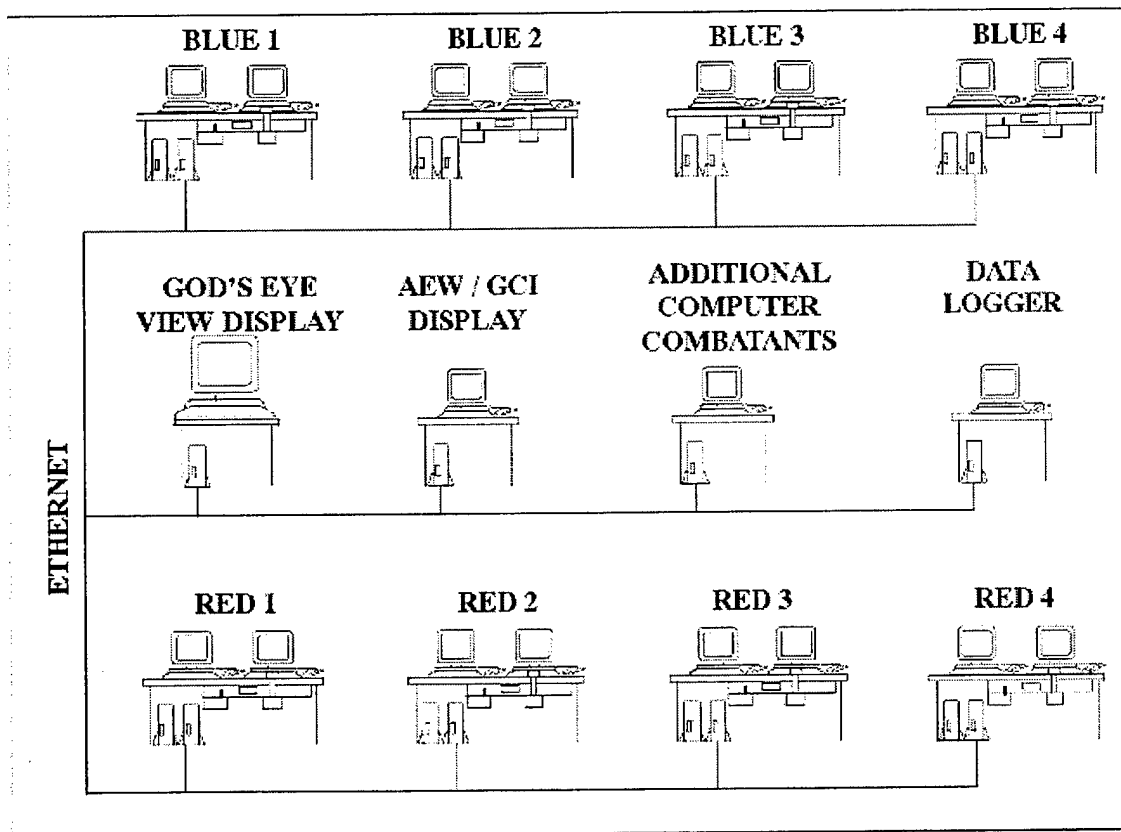
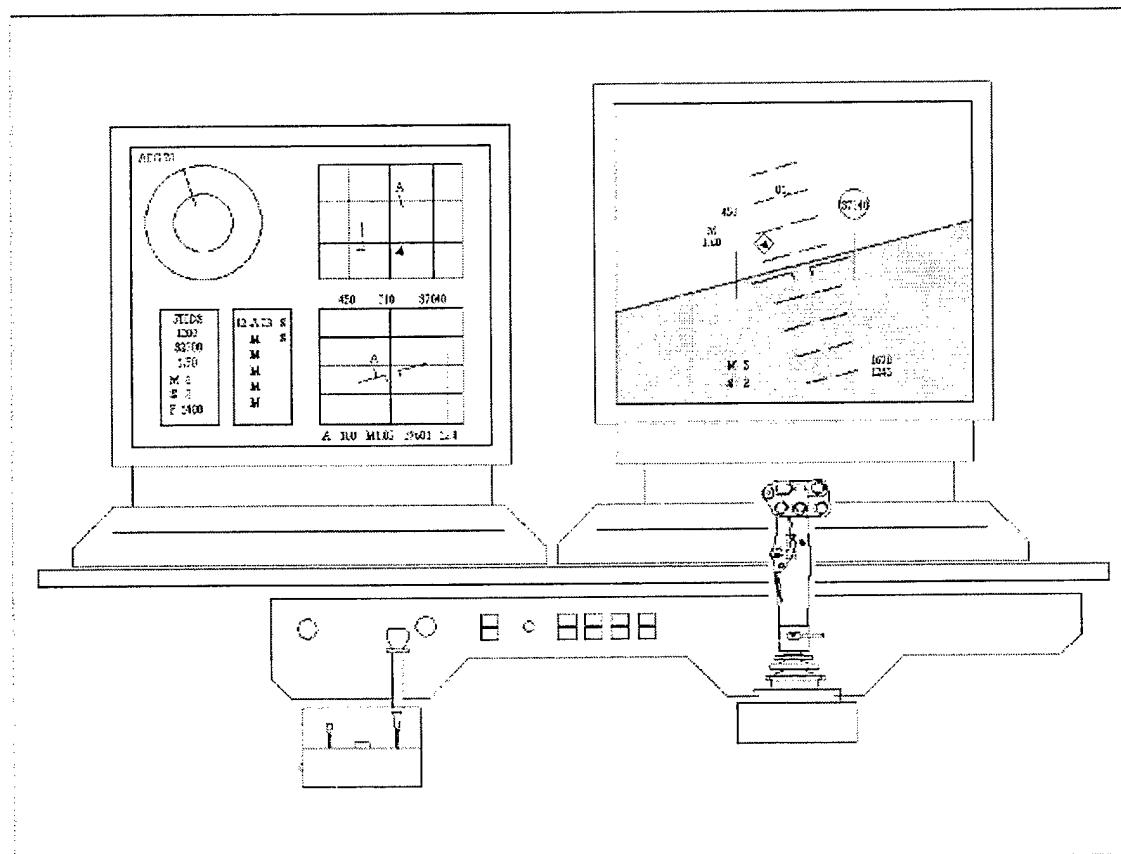


Figure 1 - Typical JOUST system configuration.

Figure 2 - JOUST system cockpit configuration.



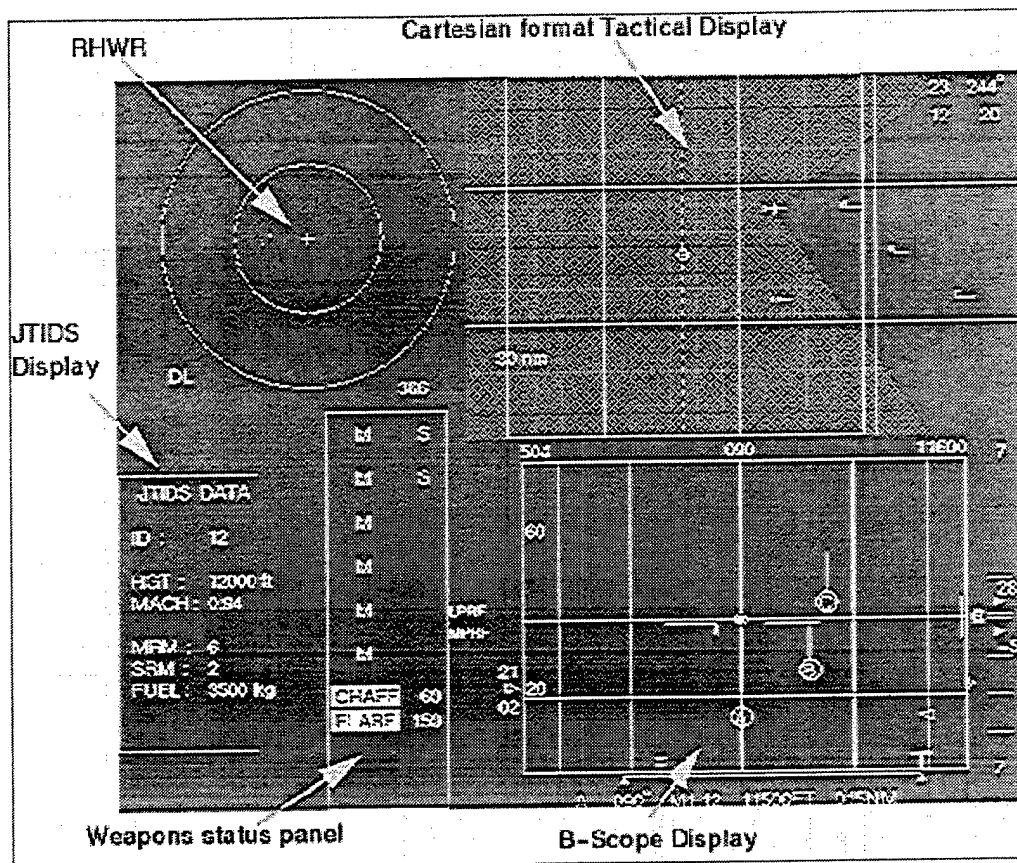
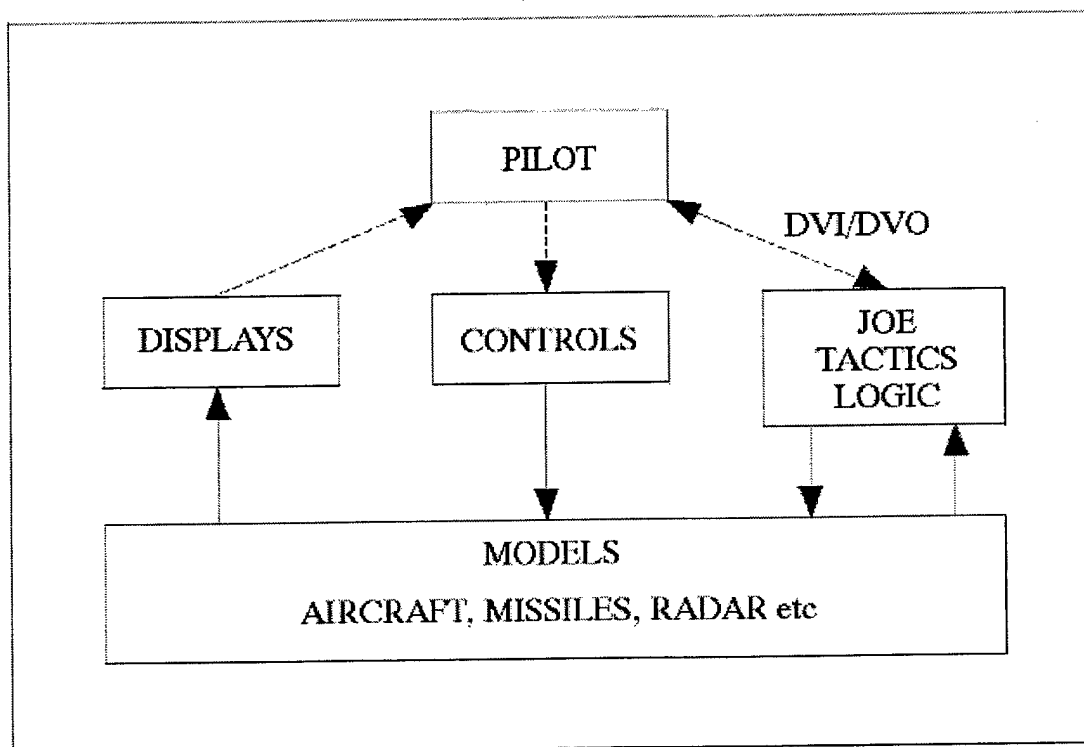


Figure 3 - JOUST system head down instrumentation.

Figure 5 - RITA Architecture



# **Robust Speech Recognition Interface to the Electronic Crewmember: Progress and Challenges**

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## **SUMMARY**

Speech is a natural form of communication between humans. It should come as no surprise that it would also be the ideal form of communication between a pilot and an electronic crewmember. High-level commands spoken by the pilot would be interpreted and carried out by the electronic crewmember in much the same way that a pilot would talk to another crewmember. The realization of this natural interface will depend on a robust speech recognition capability to handle the degraded speech conditions typical of the military aircraft environment. This paper reviews the latest progress in robust speech recognition research and its potential application for military aircraft. Sources of degradation in the speech signal will be discussed along with the techniques being explored to reduce their effects on speech recognition. Results of recent flight testing will also be presented to provide a benchmark of the performance of commercially available speech systems in the military environment. Finally, remaining challenges to providing a fully capable, high-accuracy speech interface to the electronic crewmember will be discussed.

## **1 INTRODUCTION**

Speech technology holds the promise of providing a natural means for human crewmembers to communicate with their future electronic counterparts. Automatic speech recognition is a rapidly emerging human-computer interface technology that will provide a safe and efficient method for handling the complex information management requirements of future fighter aircraft. The Vehicle-Pilot Integration Branch in Wright Laboratory (WL) has been actively investigating the potential of this technology for over twenty years. Flight test experiments conducted in the 80's provided the first opportunity for WL to assess recognition performance of first generation airborne speech recognition systems (ref. 1, 2). Results from these early flight test programs suggested that significant improvements in the area of robust speech recognition were needed before an operational system could be

fielded in military aircraft.

*Robustness* refers to the ability of a speech recognition system to operate under adverse conditions. In the military environment these adverse conditions are concentrated in two areas: noise and speech variability. Noise is produced by the aircraft engines, wind, environmental control system, oxygen mask breath noise, and electrical channel noise produced by distortion in the microphone and avionics systems. Speech variability is primarily caused by g forces, workload stress, fatigue, and Lombard speech. Lombard speech occurs when speakers attempt to make themselves heard over the background noise. If speech recognition is to be a viable cockpit information management technology, researchers must fully understand the factors that degrade the speech signal in the operational environment and develop robust algorithms to compensate for them.

Fortunately, significant progress has been made in robust speech recognition since those first flight test experiments in the 80's. Improvements in digital signal processing technology are resulting in relatively inexpensive speech recognition systems that are designed to operate in noisy industrial environments for command-and-control and data entry applications. Also, the growing market for computer telephony applications is resulting in technology capable of recognizing speech over noisy telephone lines. With little modification, a system designed for these commercial applications could be adapted for use in military aircraft.

This paper reviews the latest progress toward achieving a robust speech recognition interface for military aircraft. Sources of degradation in the speech signal will be discussed along with the techniques being explored to reduce their effects on speech recognition. Results of two recent WL flight tests on two NASA OV-10 aircraft will also be summarized to provide a performance benchmark of commercially available speech systems in the airborne environment. Finally, remaining challenges to providing a fully capable, high-

accuracy speech interface to an electronic crewmember will be discussed.

## **2 SOURCES OF COCKPIT SPEECH DEGRADATION**

As mentioned above, there exists two primary areas that can degrade the speech signal in the military aircraft environment: noise and speech variability. Each of these sources along with ways of compensating for them is discussed below.

### **Noise Sources**

Three major noise sources that contribute to degradation of the speech signal in a cockpit are ambient background noise, channel noise, and speaker noise. Ambient background noise is produced by the aircraft engines, environmental control system, and the sound of air moving past the aircraft. Channel noise refers to the distortions produced by the microphone transducer and electrical noise conducted in the wiring to the speech system. Speaker noise refers to non-vocabulary speech sounds such as lip smacks, breath noise from an oxygen mask, or grunting sounds produced when a pilot undergoes high-g maneuvers.

Three of the most commonly used techniques for reducing the effects of these noise sources are training in the environment, preprocessing, and noise cancellation algorithms. If the noise source is relatively consistent and steady-state, as it is for many airborne environments, then having the speaker train the system in noise conditions that simulate the actual aircraft environment is one method of producing representative voice templates that will more closely match commands given in flight. Preprocessing and noise cancellation are preferred over training in noise, however, as these techniques try to reduce noise effects by modification of the speech signal rather than requiring additional training from speakers (ref. 3, 4).

Oxygen mask breath noise is a unique problem that has to be dealt with for high-performance aircraft applications. The creation of breath noise models was successfully used with the ITT VRS-1290 speech system during the second OV-10 flight test experiment conducted by Wright Laboratory and will be discussed in the next section. Training the system with the oxygen mask also incorporates the intra-utterance breath noise as part of the word models and minimizes its impact.

Other speech noises such as lip smacks, grunts, or out-of-vocabulary utterances are more difficult to deal with. One method is to adjust the recognition threshold of a system to reject out-of-vocabulary sounds. The

problem with doing this, however, is that there is a danger of the system rejecting too much valid speech as well. Another method is to incorporate "garbage" models that recognize and reject speech noises and out-of-vocabulary speech. This is typical of word-spotting systems that can recognize keywords in a continuous stream of speech.

### **Speech Variability**

The second major area of speech degradation occurs when the pilot's voice changes due to various factors such as g forces, workload stress, fatigue and the Lombard effect. In previous flight test experiments, flying up to 6 g's resulted in little degradation in speech recognition performance (ref. 2). Fortunately, there is very little application for speech recognition above 6 g's and with the proper closed-loop feedback of g level to the speech system, the vocabulary and grammar structure can be significantly limited to only enable those few tasks that a pilot may want to access by voice.

The effect of background noise alone on speech recognition performance is not as detrimental as how the noise affects a speaker's response to it. This Lombard effect, named after the French physician who first described its characteristics (ref. 5), results in changes to a speaker's voice such as increased vocal effort, greater duration of words due to an elongation of vowels, frequency shifts, and deletion of certain ending consonants. While this effect makes it easier for humans to communicate in noise, it can reduce speech recognition accuracy by as much as 25 percent. The best techniques for minimizing Lombard speech are providing good audio feedback in the speaker's headset, minimizing the noise through the use of active noise reduction, and feedback techniques that provide the speaker with the gain level the system is receiving (ref. 6, 7, 8).

## **3 OV-10 SPEECH RECOGNITION FLIGHT TESTING**

To assess the impact of these various sources of speech degradation on commercially available speech recognition systems, two flight test experiments were recently conducted by WL on two NASA Lewis Research Center OV-10 test aircraft. The objectives of these experiments were 1) measure live recognition performance in several ground and flight test conditions, including testing up to 4g's and 2) generate a digital speech database for further research.



## Experiment 1 - ITT VRS-1290 Evaluation with an M-162 Boom Microphone

Sixteen subjects, comprised of active duty military and NASA pilots, participated in the evaluation of an ITT VRS-1290 speech recognition system installed in a ruggedized IBM-PC. The aircraft used for this experiment was an OV-10A aircraft operated by NASA Lewis Research Center in Cleveland, OH (Figure 1). This aircraft was a twin engine, two crew member, tandem seating turboprop aircraft. The OV-10A was capable of pulling up to 5.5 gs, but due to equipment constraints the test profiles were limited to 1 and 3g maneuvers.

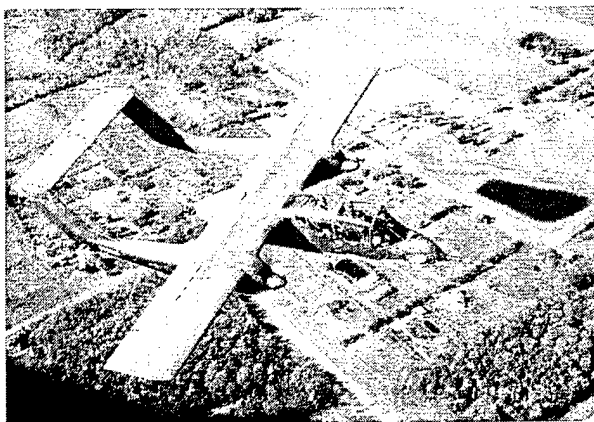


Figure 1. NASA LeRC OV-10A Test Aircraft

### Vocabulary/Grammar Structure

The vocabulary consisted of 53 words and phrases that represent various tasks that could be accomplished in a military aircraft. The vocabulary and grammar structure is shown in Table 1. The 53 vocabulary words and phrases were combined to form 91 test utterances to be used during ground and flight test conditions. Synonymous words such as Go-to, Display, and Show or page and layer were designed into the test vocabulary to allow a more flexible interaction with the speech system.

{North/South/East/West} (0 - 1 8 0) degrees (0 - 5 9)  
point (0 - 9 9) minutes

Range {five/ten/twenty/forty/eight/one-sixty/two-forty}

Give-me {TF/TA/TF-TA/ground-map/pencil-beam/  
weather/beacon}

Change Radar-mode [to] {TF/TA/TF-TA/ground-map/  
pencil-beam/weather/beacon}

{Delete/Modify} N-R-P (0 - 9 9)

Add-New N-R-P {before/after} (0 - 9 9)

{Goto/Display/Show} {IDS/comm/flight-  
director/radar/flight-plan} {page/layer}

Table 1. Flight Test Vocabulary/Grammar

### Test Procedures

Each subject began the experiment by performing template generation followed by a baseline performance assessment. Template generation involved the subjects' speaking a number of sample utterances which were prompted by the ITT system. Once template generation was completed, a recognition test followed which consisted of reciting 91 utterances twice to collect baseline recognition data. All of the laboratory training and testing utterances were recorded on digital audio tape (DAT) to allow subsequent testing on the ITT system or testing of a new speech recognition system.

The subsequent test sessions were conducted on the aircraft both on the ground with no engines running and in the air. During data collection, subjects sat in the rear seat of the OV-10A and were prompted with a number of utterances to speak. All prompts appeared on a 5" x 7" monochromatic liquid crystal display in the instrument panel directly in front of the subject. The ITT system attempted recognition after each spoken phrase with the results stored for later analysis. Once again, DAT recordings were made of the entire data collection session. After the ground test was complete, the subjects flew the flight test profile consisting of three conditions: 1) straight and level flight (1G1), 2) 3g flight (3G), and 3) repetition of the 1g condition to examine potential fatigue effects (1G2).

### Results

During the first several flights, ITT word accuracy was around 55%. In the course of investigating potential causes for this performance degradation, several problems were discovered. These problems were primarily audio related but also had to do with several engineering parameters that controlled the ITT system. After consultation with ITT researchers, DAT flight test recordings were replayed into the system on the ground with systematic adjustments to the gain and engineering parameters. Recognition performance was then obtained at greater than 98%. Once this performance optimization was accomplished, live performance was maintained at 98% or better across all flight conditions with no significant degradation at 3g's.

Due to the audio and system problems encountered during the experiment, only five of the sixteen subjects

had valid real-time recognition performance data in-flight. Four of the sixteen subjects experienced problems with the DAT recording equipment, resulting in unusable or non-existent audio data. Audio recordings were successfully collected for a total of twelve subjects in the study.

The data analyses were done in two stages. The first stage involved a comparison of "live", in-flight word recognition performance with word recognition performance obtained by playing the DAT recordings made in-flight into the ITT system back in the laboratory. The premise was that if no significant differences were found between live vs. DAT performance on the five subjects that flew with the optimum configuration, then the remaining subjects with complete DAT audio could be retested in the lab in the same way. Figure 2 shows the mean word recognition performance for both live and DAT recordings for the five subjects who had valid in-flight data.

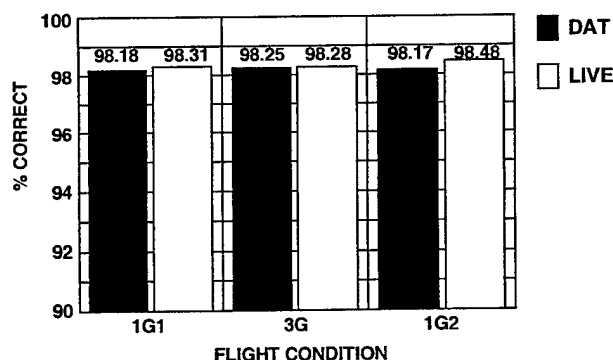


Figure 2. Mean word accuracy for live and DAT testing

An Analysis of Variance revealed no significant differences in word recognition performance when providing the ITT system with both live and digitally recorded audio signals. With no performance differences found between live and DAT audio signals, all of the remaining analyses were done using DAT audio tape as the input to the VRS-1290. This provided complete recognition data for twelve subjects. Figure 3 shows the mean word recognition performance obtained for each of the test conditions. Statistical analysis revealed no significant differences in any of the test conditions.

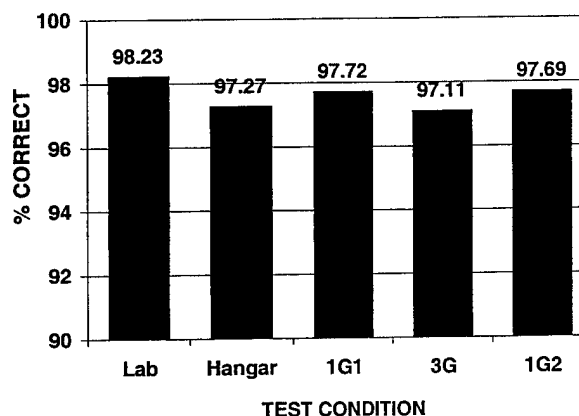


Figure 3. Mean word accuracy for each test condition.

### Experiment 2 - ITT VRS-1290 and Verbex VAT31 Evaluation with an M-169 Oxygen Mask Microphone

A second experiment was conducted, this time using an oxygen mask with an Air Force standard M-169 microphone to examine the effects of aircraft noise, breath noise and g's on speech recognition performance. Ten subjects participated in the first stage of the experiment which evaluated the ITT VRS-1290 speech recognition system, this time installed on a NASA OV-10D aircraft. After the ITT testing was completed, a Verbex VAT31 was installed and evaluated with six subjects using the same vocabulary and grammar structure. Since different subjects were used for both systems, a direct comparison between the ITT and Verbex was not performed. Also, both ITT and Verbex were consulted to ensure optimum performance for both systems.

### Vocabulary/Grammar Structure

A new vocabulary and grammar structure was developed for this experiment. The vocabulary consisted of 47 words and phrases, some of which were used during the second AFTI/F-16 flight test that was performed over ten years ago (ref. 2). The vocabulary and grammar structure is shown in Table 2. A total of 57 test utterances was developed to be used during ground and flight test conditions.

(Uniform/Comm 1) (2 0 0 0 - 3 9 9 9)  
 (Victor/Comm 2) (1 5 0 0 - 1 9 9 9)  
 (Uniform/Comm 1) (button/channel) (1 - 2 0)  
 (Victor/Comm 2) (button/channel) (1 - 2 0)  
 Radar range (ten/twenty/forty/eighty)  
 Radar azimuth (ten/thirty/sixty)  
 Radar (1/2/3/4) bar  
 (HI-TACAN/ILS) runway (0 0 - 3 6) (Left/Right)

(Say/Whats-my) (fuel/inventory)  
 (Tracker/Targeting-pod) (wide/narrow/cursor-zero)  
 (Tracker/Targeting-pod) (black/white) hot  
 CCIP  
 Air-to-air-mode  
 Air-to-Ground-mode  
 Nav-mode  
 Strafe

Table 2. OV-10D Flight Test Vocabulary

## Test Procedures

The test procedures for both the ITT and Verbex systems were repeated from the first experiment. Each subject began the experiment by performing template generation followed by a baseline performance assessment. After that, a recognition test followed which consisted of reciting 57 utterances twice to collect baseline recognition data. Once again, all of the training and testing utterances were recorded on DAT to allow follow-on testing.

The subsequent test sessions were conducted on the aircraft both on the ground with no engines running and in the air. After the 114 utterance ground test was complete, the subjects flew the flight test profile consisting of three conditions: 1) 114 utterances at straight and level flight (1G1), 2) 70 utterances in 4g flight (4G), and 3) 114 utterances repeating the 1g condition at a higher engine throttle setting to induce more noise for this condition. (1G2).

## Results - ITT Testing

Due to various data recording and aircraft problems, DAT audio was successfully recorded for only eight of the ten subjects under all test conditions. Live recognition performance was obtained for five of these eight subjects. Figure 4 shows the word accuracy for five subjects under each test condition. Two factors accounted for the majority of the recognition errors, lack of automatic gain control and Lombard effect. As a result of the first flight test, the ITT system was used without its automatic gain control circuitry enabled. This was because the ITT system had difficulty converging on the proper gain setting when exposed to high noise. Also, when it finally did settle on a particular gain setting, it was found that the signal was too strong to obtain accurate results. So fixing the gain to a predetermined value was the only way to get the ITT system to function reasonably well in this second flight test.

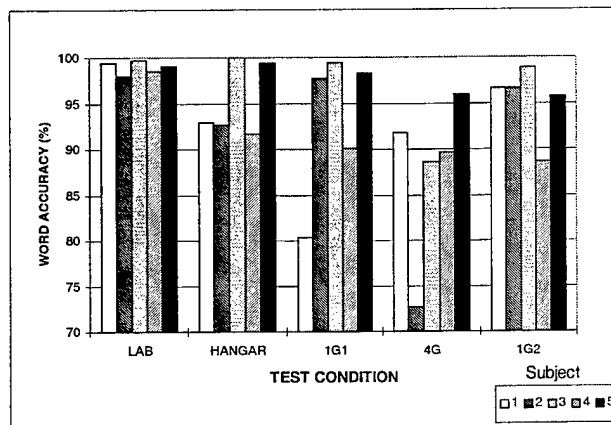


Figure 4. ITT word accuracy for five subjects

This became a problem, however, with subjects that had a pronounced Lombard effect, particularly in the 4G condition. During the 4G run, the noise level increased by an average of 22 dB from the 1G1 condition. This, coupled with a lack of good sidetone in the subjects' helmet earcups, resulted in some subjects almost shouting to compensate for the increased noise level. This explains why subject 2's word recognition results at 4G were at 72.7%. Subject 5, however, was very accustomed to speaking in the OV-10 and consequently was able to maintain performance at 95% or better for all conditions. Average performance over the five subjects was 97.2% for the two ground conditions and 92.1% for the three flight conditions. Subsequent experiments are planned with the DAT audio to determine if gain normalization will improve ITT performance.

## Results - Verbex Testing

Five of the six subjects had complete live data and DAT audio for each of the five test conditions. Figure 5 shows the live word recognition performance for each of the five subjects. Subject 5 is the same subject as subject 5 in the ITT test. Due to his experience with both the aircraft and the testing procedures, his performance was the best at 100% under all conditions. Subject 3 was a non-pilot subject that showed a pronounced Lombard effect under 4g's. This explains the performance degradation of 86% in the 4G condition. Overall, the system achieved an average word accuracy of 99.5% in the ground conditions and 97.3% in the flight conditions.

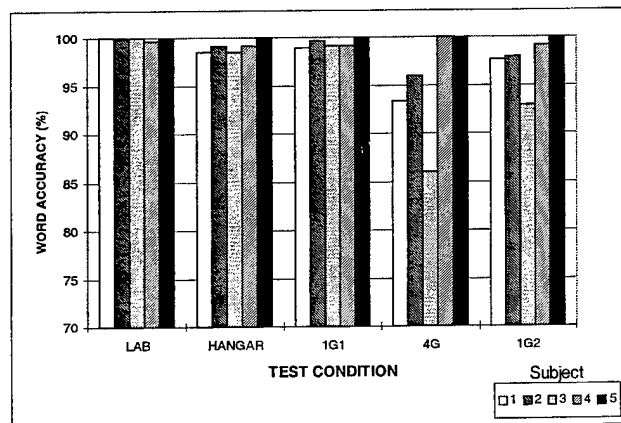


Figure 5. Verbex word accuracy for five subjects

### OV-10 Flight Test Conclusions

The two flight test programs summarized here provided an excellent opportunity to obtain practical experience with the airborne evaluation of commercially available speech recognition systems. Perhaps of greater significance than the actual recognition results, however, is the fact that an extensive digital speech database was recorded that will be distributed to other speech recognition researchers to develop and evaluate recognition algorithms for the airborne environment. This database will also be used internally to evaluate other candidate speech systems without going through the expense of additional flight testing. Of particular interest is the evaluation of several speaker independent systems that do not require training prior to use.

### 4 FUTURE DIRECTIONS AND CHALLENGES

A robust speech interface in the cockpit is fast becoming a cost effective technology option for crew systems designers. With digital signal processing speed increasing about 20 percent each year, the necessary horsepower required to provide high accuracy, real-time speech recognition in the military environment is already here for small vocabulary, continuous speech command and control applications. With the latest push to adopt commercial technology for military use, the Air Force can leverage a tremendous investment by commercial developers working on robust speech interfaces to automobile systems, cellular telephone dialing, information kiosks, personal digital assistants, etc. While none of these environments can fully compare with the operational fighter environment, technology gains made in the private sector will have direct application to the military.

Several new approaches to improving robust speech recognition are also showing a lot of promise in the

laboratory. Researchers are exploiting the use of neural networks for improved pattern recognition and auditory modeling techniques that mimic the excellent noise filtering characteristics of the human auditory system (ref 9, 10).

Once this robust speech processing capability is available, the remaining challenges lie in the application designer developing a natural, intuitive interface between the pilot and the electronic crewmember. Speech understanding systems that are able to interpret meaning from spontaneous conversational speech input are still in their infancy. Fortunately, fighter pilots have little need for verbose discourse with their aircraft and would rather communicate in very short, unambiguous commands. No other human-computer interface technology has the potential for providing as rapid and efficient an interface, allowing the pilot to respond to mission events at a higher level of control and provide the timely decision support needed to return home safely.

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# **Human-Electronic Crew Communication: Applications for Speech Recognition in the Cockpit**

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## **1. SUMMARY**

The concept of an electronic crew-member (EC) and its application in US Air Force aircraft has been considered for many years. The details of implementing this concept are divided among various groups of people. One such group comprises the artificial intelligence programmers who struggle with the transition of knowledge into software code. Another group, pilots who would provide the knowledge base for the EC, are concerned with always maintaining "command" of the aircraft. Finally, the cockpit design group struggles with designing an optimum interface between the pilot and the EC. It is from this third viewpoint that the methods by which the pilot and the EC might potentially communicate with one another will be discussed.

This paper examines the current method of facilitating communication between the pilot and computers on board the aircraft, as well as some futuristic ideas for communication. One such method, which is the focus of this paper, is speech recognition and feedback. The integration of this technology into a fighter aircraft application, as well as lessons learned in laboratory simulation will be discussed.

## **2. INTRODUCTION**

Pushing buttons or switches in the cockpit is the current method by which the pilot and the computers on-board the aircraft communicate. Whether the switches are bezel-mounted around a Multi-Function Display (MFD) or on the throttle and stick, pilots must master location and control logic sequence to make changes to the cockpit setup. Having command of on-board systems via the stick and throttle is a very attractive concept because the pilot can maintain control of the aircraft while still exercising various options in the cockpit. This concept, referred to as

Hands On Throttle And Stick (HOTAS) operation, is present in most of the US Air Force's fighter aircraft (Ref. 1).

With continuing exponential growth in computer technology, a corresponding growth in cockpit subsystem functionality is also expected well into the future. Aircraft computers will be able to process more on-board information as well as accept vast amounts of data from off-board sources such as Airborne Warning And Control Systems (AWACS), satellites, ground controllers, a wingman, etc. As the amount of data coming into the cockpit increases, stick and throttle designers will soon run out of space on these controls to integrate more switches. With this potential increase in the amount of data, a new interface that complements the HOTAS concept will be needed to facilitate operation of future aircraft.

## **3. NEW EC INTERFACE CONCEPTS**

The use of a touch sensitive overlay on display surfaces has been investigated as an alternate way of communicating with on-board computers. Touch control is a very intuitive method of operation – little training is needed for one to be able to master this type of control in a short period of time. Touch control has been tested in a number of applications. Liggett, Kustra, and Reising (Ref. 2) showed that for a target designation task, touch control provided faster response times than the target designation control on the throttle (standard method of designating targets in fighter aircraft). However, other research has shown that pilots expressed concern about the use of touch control in terms of accidental touches, response time, and loss of tactile feedback (Ref. 3). Additional concerns include the potential for visual parallax, and more importantly, the use of such a system when pulling Gs. Obviously, if fighter pilots are in a 7 G turn, they won't be lifting

their hand to touch their MFD because the g-loading will be too extreme to do so.

Touch control is attractive because it is so intuitive. Even more intuitive might simply be *looking* at items of interest and communicating with the cockpit in this manner. Two types of controls that fall into this category are eye and head tracking. Eye tracking consists of equipment that reads the pilot's retinal location to determine where the eye is focusing. This can be achieved with an infrared corneal reflective system (Ref. 4). Head tracking consists typically of a magnetic or ultrasonic unit that is attached to the pilot's helmet and sends information to the computer as to the position of the head.

If we take the intuitive control logic one step further, instead of looking at an area of interest, one might just think about it. Thought control, achieved from electrical impulses taken from the brain's neurons (Ref. 5), is being investigated as a possible control method for future applications. This type of control mechanization, however, is years away from being incorporated into a cockpit.

### 3.1 A Near Term Solution

One type of control and display method that has been getting much attention lately is voice interaction. Voice interaction usually consists of speech recognition paired with *audible* feedback, although *visual* feedback is often provided after receipt of a speech command. The following sections discuss how the technology might be used, what its advantages are, and how well it has been performing in recent flight tests.

In the normal course of flight, pilots wear a headset or oxygen mask and microphone to communicate with other crewmembers, air traffic control, a wingman, AWACS operators and others. Communicating with the computer via a voice control could be just as natural as talking to any other crewmember. Also, speech recognition and feedback allows pilots to maintain control of the aircraft by keeping their hands on the stick and throttle while communicating with the aircraft.

Controlling aircraft systems, receiving information from on-board computer systems, and managing off-board data can all be done much more safely and efficiently using voice control. For example, one voice command can replace a number of button pushes to access layered pages on an MFD, a task that currently *increases* the pilot's manual and visual task load, and *decreases* "head-up" time. Anything

that can be accomplished by a button push can also be done by the voice system. Other potential applications include asking the computer to display or remove information on the instrument panel, configuring the cockpit displays for a specific mode of flight, obtaining a verbal message of the amount of fuel on board, and receiving verbal messages regarding distances to targets. The voice system would be a natural interface to the mission computer to achieve data entry and data retrieval.

The advantage of this type of control is that it allows pilots to use the modality of speech, which is in many instances not as overworked as are the visual and manual modalities. In addition, speech recognition systems allow for increased eyes-out operation. This can result in improved situational awareness, especially for the single-seat fighter pilot.

One of the biggest challenges in voice control is ensuring the system's robustness in the dynamic aircraft environment. Early flight testing of voice control systems (Ref. 6) showed a lack of technology maturity, requiring the pilot to speak slowly and artificially to the system. Flight tests in rotary wing aircraft a few years later (Refs. 7 and 8) began to demonstrate the emergence of continuous speech recognition with higher recognition accuracy, but showed other problems such as high levels of aircraft noise being recognized as speech (referred to as false alarms). Recent flight testing, however, has demonstrated that accuracies as high as 99% are attainable with commercial speech systems at noise levels as high as 120 dBA. (Refs. 9 and 10).

These recent successful flight test results established the viability of speech recognition systems in an actual aircraft environment. Simply attaining acceptable word recognition accuracy with any benign vocabulary, though, does little to reduce pilot workload and increase mission effectiveness and survivability. Considerable effort must be dedicated, before fielding a system, to determine the mission requirements for speech recognition, to develop a vocabulary and syntax that will support these needs, and to optimize the vocabulary for increased accuracy and mission effectiveness.

### 3.2 Developing a Fighter Aircraft Application

The process of developing a vocabulary and syntax for a fighter aircraft application is a rather time-consuming one involving a number of iterative phases, as outlined in Figure 1. All phases might be accomplished two or more times, with each resulting in a further refinement of the vocabulary and syntax.



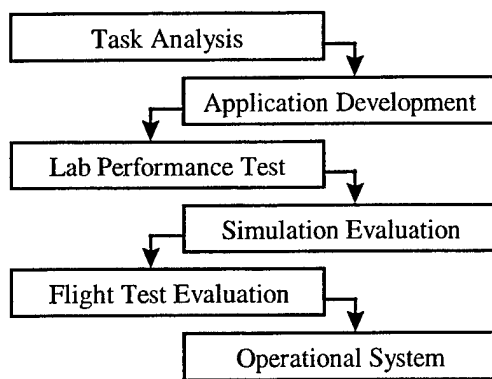


Figure 1. The Syntax Development Process

The first step entails an analysis of the tasks to be performed in order to identify instances when the pilot's hands and eyes might be busy. It is during these instances that using the speech channel would be ideal. Once the candidate mission tasks are identified, a syntax design team generates a list of candidate vocabulary words or phrases that accomplishes those tasks. The design team may consist of software programmers, human factors engineers, and pilots. The team combines candidate words to form a syntax to be used by a speech recognition system. During the later stages of the development process, the selection of a particular speech recognition system might be based upon the attributes of the chosen vocabulary. For example, some systems are known to be better at continuous digit recognition. Other systems might excel at filtering background noise.

Once a preliminary vocabulary and syntax application is developed, it should be taken to the user community to demonstrate its potential usefulness. Feedback from the user community refines the terminology to adapt local jargon.

The refined syntax is then taken to the laboratory for a test of robustness. Ideally, members of the user community serve as subjects in the first tests of the vocabulary, but because of time, budget, and other constraints, volunteers from available subject pools are more commonly used. One or more speech recognition systems may be tested to determine the best one to use for the application being tested.

After laboratory testing, refinements are again made to the system in preparation for a more formal test in a simulated mission scenario. These tests involve members of the fighter pilot community. Simulated missions are flown in an attempt to evaluate the

recognition system's ability to accurately carry out the pilot's command. In addition, both subjective and objective data are collected to measure the effectiveness of using speech recognition to perform the mission tasks. Other ground-based simulations might be conducted to evaluate the effects of other environmental variables, such as noise, on the recognition system. Once ground-based simulation is completed, the proposed system is taken to flight test, where other environmental variables such as Gs, vibration, stress, etc. are present. The results of flight test determine if these variables significantly affect recognition performance.

The Vehicle-Pilot Integration Branch within the US Air Force Wright Laboratory has recently completed much of the work needed to accomplish a high fidelity flight test of a speech recognition system in an F-16 research aircraft. A candidate vocabulary has been developed, laboratory tests were conducted using the recognizer to be installed in the aircraft, and a first simulation effort has been completed to solicit ideas and comments from the fighter pilot community. The following sections highlight the findings of the laboratory and simulation tests.

### 3.2.1 Laboratory Test of a Candidate Vocabulary

A representative fighter aircraft vocabulary was developed and implemented on a Verbex speaker-dependent speech recognition system to determine the effects of multiple testing sessions on recognition performance. It was hypothesized that by using the system over a period of 5 days, subjects would become increasingly comfortable and consistent in their use of the system, resulting in better recognition accuracy.

Twelve male Air Force military and civilian volunteers served as subjects for the laboratory test. Approximately half of the subjects had participated in at least one prior experiment involving speech recognition, although the average experience with this technology was less than two hours.

The vocabulary developed for this effort consisted of 90 words (Table 1) which describe tasks performed by fighter pilots during a typical air-to-ground weapon delivery task. The words were combined to form 91 unique phrases used to prompt the subjects during the test.

Subjects were first briefed on the nature of the study and then seated in front of a computer monitor to begin the task of "training" the recognition system to recognize their voice. This template training session,

0	1	2	3
4	5	6	7
8	9	Accept	ADI
Air-to-Air	Air-to-Ground	Arm	Bottom
Chaff	Circles	Clear	Create
Cue	Cuer	Data	Declutter
Designate	Display	DOI	East
eight	eighty	eleven	Engine-Fuel
Engine-Weapon	Enter	fifteen	five
Flares	forty	four	four-point-seven
fourteen	Freeze	Hi-Res	JDAM
Left	Map	Mark	Maverick
mode	Narrow	Nav	New
nine	North	one	one-sixty
PFD	Pitch-Fault	point	Radar
Range	Real-Beam	Report	Reset
Right	Route	Safe	seven
six	Slew-Next	South	Steerpoint
Systems	System-Status	Target	Targeting-pod
ten	thirteen	three	Top
TSD	twelve	twenty	two
Uniform	Update	View	Weapons
West	Wide		

Table 1. Laboratory Test Words

which is required of all speaker dependent systems, typically lasted 20 minutes. Once template training was completed, the first of 5 data collection trials of the test was completed. Subjects were visually prompted via the computer monitor to speak each test prompt, presented one at a time in random order. The subject's task was to simply speak the phrase shown on the computer screen while the speech system attempted recognition of the utterance. While only 91 unique phrases were developed for this test, a total of 227 phrases were presented during each trial. Many of the unique phrases were repeated in an effort to collect at least 5 utterances of each vocabulary word.

The test trial lasted approximately 20 minutes. On the three consecutive days immediately following the training and first trial session day, subjects were required to come back to complete another trial of speaking 227 test prompts. The fifth and last trial was run exactly 10 days after completing the first

trial. Results were scored for word recognition accuracy

Adjusted Overall Accuracy (AOA) (Ref. 11) was computed by trial, as shown in Figure 2. In general, word recognition accuracy for this vocabulary / recognizer combination were on the order of 99%, which was considered to be acceptable for the rather "sterile" laboratory conditions of low noise, low stress, and high signal-to-noise ratio of the audio signal to the system. There were no statistical differences in recognition accuracy among the individual trials, indicating that subjects neither gained nor lost recognition accuracy over time.

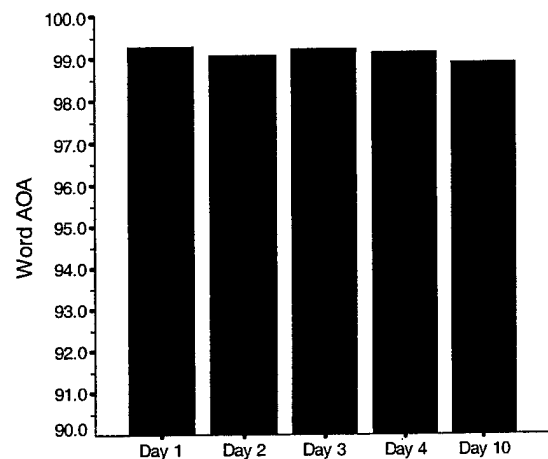


Figure 2. Laboratory Test Results

The ability of subjects to train the recognition system in less than 30 minutes, attain high recognition accuracy with the selected vocabulary / syntax, and maintain accuracy over a period of days proved the viability of the system to be used in the more costly and time-consuming aircraft simulation tests to follow.

### 3.2.2 Simulation Test of the Candidate Vocabulary

Following the initial laboratory test of the candidate vocabulary, an aircraft simulation test was conducted, during which USAF, USAF Reserve, and Ohio National Guard subject pilots provided additional input to the vocabulary and syntax design.

The primary objective of the simulation was to further refine the vocabulary and to determine the potential mission effectiveness of using speech recognition technology during a simulated air interdiction mission.

Twelve male current and former military pilots participated in the simulation. All pilots had at least 200 hours of experience in modern fighter aircraft (A-10, F-15, F-16, F-18, F-117).

Each of the subject pilots participated for six to eight hours of testing conducted over a two-day period. The simulation scenario required the pilots to fly eight low-altitude interdiction missions, originally planned to destroy an enemy tank column and a petroleum / oil / lubricant (POL) site. During the missions, pilots were re-directed to destroy enemy aircraft parked on an airfield.

Each of the eight simulated flights contained three segments in which the pilot was required to perform secondary tasks in addition to the primary task of flying the aircraft. During the first segment, pilots were required to manually fly terrain following and terrain avoidance (TFTA) while changing a radio frequency, changing the planned route, and fixing a flight control fault. In the second, or target detection / acquisition segment of the mission, pilots needed to create a patch map using the synthetic aperture radar. In the third and final segment, pilots were required to designate six targets and deliver the weapons in a single pass. The secondary tasks were performed using either current manual means (push buttons and switches) or by speech recognition.

Although most objective results are still pending, preliminary findings revealed a significant decrease in the time required to perform cockpit tasks related to digital entry when using the speech recognition system. Examples of these tasks include entering latitude / longitude data to accomplish a mission reroute and entering the coordinates of a known reference in order to update the navigation system. A complete set of objective simulation results will be the subject of a future report.

The subjective comments of the pilots have also provided valuable insight as to the optimized use of speech recognition in the cockpit. Many of their suggestions, as well as the lessons learned from the implementation of the speech recognition system, are described below.

### 3.3 Lessons Learned

During both the laboratory and simulation studies, a number of lessons were learned in the development of the vocabulary and the use of the speech recognition system. The major lessons learned are summarized below.

***Pay strict attention to the engineering parameters that are available for the system.*** There are a number of engineering parameters that typically can be manipulated on most speech recognition systems. These parameters control functions like rejection threshold, noise cancellation options, number of training passes, minimum and maximum time-out values, etc. The parameters requiring most attention dealt with the amount of silence allowed between words in a phrase and the amount of silence required at the end of the phrase to signal an end of phrase event. An attempt was made to allow slower, more meticulous speakers additional time between words in a phrase, while still providing good recognition performance for "fast speakers". Setting this value to 300 milliseconds seemed to provide good recognition performance for both groups of speakers.

The rejection threshold was another parameter that consumed a considerable amount of design time. Setting the rejection threshold too low resulted in an unusually high false alarm rate, whereas setting this too high caused the system to reject properly spoken phrases. This value had to be adjusted after any vocabulary or syntax change.

One training option that was found to be quite useful was called the "integrated enrollment" option, where each word to be trained during the discrete pass was presented in a sentence. The subject had an opportunity to see the word in context before pronouncing it, which created a more solid template base for the word during subsequent continuous speech training passes for co-articulation effects.

***Shorten verbose phrases.*** Pilots in the simulation phase indicated that they wanted very short phrases or words to accomplish tasks. For example, the originally designed vocabulary required the pilots to say "Report System Status" when requesting some information about one of the aircraft's systems. Pilots suggested that they only be required to say the word "Systems" when asking for any system information. The phrase "Slew Next Steerpoint" was likewise shortened to "Slew Next". On a related topic, if the Attitude Director Indicator (ADI) could only be shown on the left MFD, then the pilots only wanted to simply utter the phrase "ADI", instead of having to say "ADI Left" in order to show that information on the left MFD.

***Continue to use HOTAS for time critical functions.*** Functions that are extremely time critical are better left on the stick and throttle. Examples include chaff

and flare dispensing, dogfight switch, weapon selection, etc.

***Don't take short cuts with the syntax.*** Take the time to program the syntax so that the resulting phrases make logical sense. For example, when programming a syntax for a UHF frequency change, only the digit words "2" and "3" should be allowed as the first words in the phrase, since all valid UHF frequencies start with a 2 or 3. The resulting logic will be more complicated, but recognition accuracy will be better by limiting the number of words the recognition system must consider.

***Use audible feedback, but keep it short.*** In general, the pilots in the simulation liked the audible responses from the voice system when asking for information, but the following guidelines were suggested: 1) All aural feedback should contain at most two words, and 2) Aural feedback should be provided only when there is no obvious visual change. For example, when switching from the air-to-ground mode to air-to-air mode, a number of obvious display changes take place, negating the need for an aural indication of the change.

***Use Voice "Macros" whenever practical.*** Pilots do not like to type in information such as communication frequencies and waypoint latitudes and longitudes. They really liked the alternative of saying the frequency and having the speech recognition systems type in the frequency for them. An even better solution would be to implement the already pre-planned frequency change (analogous to radio presets) with one simple voice command. For example, the UHF frequency "two three eight point seven five" could be coded as "blue seven". The pilot would simply say "blue seven" and the UHF radio would change to that frequency. Another "intelligent" system would allow a pilot to say "Select tanks" from an automatic target recognition system display instead of saying "Select targets one, two, seven, three, six".

***Recognize the differences between prompted and spontaneous speech.*** Many laboratory tests of speech recognition systems require subjects to speak a visually prompted word or phrase. When the prompts are removed, the subject must rely on memory and experience to effectively operate the system. With a lack of sufficient practice and experience with the system, subjects' speech is usually disfluent, resulting in sub-optimal recognition accuracy. The best speech recognition accuracy comes from well trained and experienced speakers.

#### 4. CONCLUSIONS

The cockpit research community has generally recognized the potential benefits of using speech recognition technology in aircraft. Commercial off-the-shelf speech recognition systems have proven to be extremely reliable in their ability to accurately recognize spoken commands in quiet laboratory and office environments. A number of challenges must be met, though, before systems can be fielded in operational aircraft. These systems must be proven to work in a cockpit where noise, Gs, and vibration all affect the way a pilot might speak.

Mission specific analyses of cockpit tasks must be conducted to identify instances where voice control would save time or keep the pilot from having to look down into the cockpit to enter data or retrieve information. Interviewing the operational pilot community, inviting them to see the technology in simulation, and flight testing are all excellent ways of identifying and refining potential applications of speech recognition in the cockpit. Much of this work is iterative. Changes are made to vocabulary and syntax based on user feedback, and then re-tested, which provides more feedback and hopefully fewer changes. The laboratory and simulation work described in this paper provided valuable insight into the vocabulary and syntax requirements for a typical air interdiction mission. The lessons learned from this research will be carried into flight test on the F-16 in the fall of this year.

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# Information Attributes and the Electronic Crewmember

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## Summary:

The Electronic Crewmember (EC) will not only be able to support intuitive situation awareness, but will also assist in making correct mission decisions and responses. It can do this because it develops a unified picture of emerging situations by taking a holistic view of all the information and data available in the aircraft.

The ultimate responsibility for the aircraft and the mission lies with the human crew who must therefore retain overall authority over the actions of both mission avionics and the EC. So, the human and EC form a team with common objectives but differing individual roles. As with any team that must display 'right-stuff' qualities, efficient communication and interaction between its members is essential. In the high-stress aircraft cockpit environment the interaction between the human and EC is a particularly complex activity.

In order to design efficient means of conveying information between the human and the EC, actual information must be considered together with its attributes or meta-characteristics. In this way, information can be passed round the system as a vector which also contains data about how it should be interpreted.

This paper discusses some of the attributes and meta-characteristics which are required to support the intuitive presentation of information to the crew.

## 1. Rationale for the Electronic Crewmember - a review

The benefits of incorporation of Electronic Crewmember (EC) capability into the mission avionics of military aircraft are well understood. Associated research programmes include the MMA project (UK) [1], Pilot's Associate (USA)[2], Copilote Electronique (France)[3] and CASSY(Germany)[4].

The amount of information, as well as the number of options for responses, required to carry out military missions, i.e. the scenario demand, is increasing over time, whilst the man-machine bandwidth capability remains static. This is particularly the case for the foreseeable future due to increasing proliferation of information technology systems emerging in the battlefield. The EC has been proposed as a means of organising and processing information, providing decision support and keeping the man-machine protocols within the workload capabilities of the crew with respect to the ever-increasing scenario demand.

In broad terms, the carrying out of a mission can be broken down into a number of concurrent management activities, each of which requires a particular man-machine protocol.

These include:

- \* Aircraft systems and vehicle management;
- \* Defensive systems management;
- \* Attack systems management;
- \* Weapons systems management;
- \* Communications management;
- \* Position & Time management;
- \* Sensor management.

Each of these management activities can benefit from EC functions which can offer enhancements and improvements to the:

- \* man-machine protocol (crew workload management);
- \* crew awareness of emerging total situation;
- \* correctness and efficiency of platform responses.

In order to provide for these functions, the EC needs to contain novel machine capabilities such as:

- \* data fusion and information management;
- \* situation assessment;
- \* generation of advice and decision support.

A system to support these capabilities can be built from functional components such as:

- \* sensor data fusion;
- \* situation assessment;
- \* planning;
- \* man-machine interface.

The introduction of these components gives the potential to provide information that, if correctly presented to the crew, can enable them to assimilate emerging situations more readily, and respond more effectively. If the crew interface to these underlying functions is correctly designed, it will also minimise workload associated with the assimilation of information by the crew and imply intuitive responses.

In this way, missions will continue to be able to be carried out efficiently by a small number (1 or 2) of crew, without them being significantly affected by the increasing scenario demand.

However, this can only happen if the human-EC team display 'right-stuff'<sup>1</sup> qualities.

## 2. 'Right-stuff' qualities and design issues

In considering a system to support human-EC teamwork with 'right-stuff' qualities, design goals to be taken into account must include such issues as:

- \* How to fix the level of automation in the interface to enable timely understanding whilst leaving the crew in the loop and in charge;
- \* How to ensure that the crew comprehend what is happening and are not just responding to directions they do not understand;
- \* How to achieve the right level of trust so that whilst cross-checking is encouraged, it does not take so much time as to make the system useless;
- \* How to establish what functions the crew require from an EC in terms of support and 'relationship';

... but most importantly:

- \* How to design efficient human-EC interface protocols.

The rest of this paper discusses the last of these in particular.

Achievement of these design goals will provide benefits, but not without a trade off with systematic costs. Each of them, at least to some extent, loads the requirements for the human-EC interface. So in general, the benefits of introducing EC functions into the aircraft must be considered in relation to human interface difficulties and adverse systematic side effects (or costs).

## 3. Adverse systematic side effects of the Electronic Crewmember

The behaviour of the cockpit instruments not only indicates information provided by the functions of the various avionic systems of the aircraft, but also the correct functioning and apparent quality of them. However, the EC will form an information layer between the crew and the avionic systems, whose correct functioning will no longer be able to be assumed simply by the presence or absence of displayed data.

As a generator of information from data, the very presence of the EC introduces new design requirements and considerations for its human interface. These include how to impart an understanding of attributes such as:

- \* Uncertainty;
- \* Probability;
- \* Stability;

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<sup>1</sup> These have been extensively discussed (e.g. [5]), and form measurable high level objectives or drivers for the design of the human-electronic crewmember system.

## \* Assumptions.

Effectively, these attributes form meta-characteristics and are the qualitative glue which bind the human and the EC into a tight and effective team with 'right-stuff' qualities. The result is that each piece of information, combined with its meta-characteristics forms an information *vector*.

Meta-characteristics contribute not only to the opinion the human has of the system, but also vice versa. How can the machine *know* whether the man is giving it flawed information? A mission database may be loaded at the beginning of the mission and may easily contain uncertain and incomplete knowledge and assumptions.

The following examples indicate situations where these meta-characteristics come into play to varying degrees:

**e.g.1:** EC: "There might be a SAM site over there somewhere"; "Or is it a tank?"; "Oh no there isn't"; "Oh yes there is"; "What do you think?"

**e.g.2:** EC: "I'm sure there is a SAM site over there and I think it's a SAM-13"

**e.g.3:** EC: "There is a SAM site at co-ordinates (x,y) and based on its behaviour, it is very probably a SAM-13"

**e.g.4:** EC: "That area over there is highly threatening because of SAM-13 presence, it may only be navigated under 200ft, and even then with difficulty. Your route currently goes through it, and mission success has been reduced to 30% as a result. There are less costly routes possible; would you like to see them?"

In all the information presentations shown, varying degrees of side effect parameters are indicated. These side effect parameters introduce a new set of design challenges and considerations for the crew interface.

## 4. Matching system functionality to crew capabilities and requirements

Introduction of EC technologies introduces new design considerations. For an effective crew interface these fall into four major categories:

- \* The ability of the system to present the information;
- \* The ability of the crew to assimilate the information;
- \* The requirement for trustworthy<sup>2</sup> information;
- \* The ability of the human to question and cross-check the validity and sources of the information.

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<sup>2</sup> Trustworthy in terms of both reliability of underlying systems as well as from a human-EC teambuilding point of view.



In turn, the quality of the provision of these major factors depends on several issues:

- \* Amount of information present and cockpit location constraints;
- \* Reliability: integrity, fidelity and quality of information;
- \* Stability of information;
- \* Completeness of information;
- \* Aircrew trust;
- \* Human limitations.

#### **4.1 Amount of information present and location constraints**

With the advent of new avionics capabilities, the amount of information potentially available for display in the cockpit is ever increasing. The provision of the EC could be seen as contributing to this increase. In highly volatile and dynamically unfolding situations 'situational ballooning' can occur, where the number of options to be costed and created by the EC increases at a higher rate than the number of scenario considerations to be taken into account.

At the same time, however, the EC can provide functions to manage and prioritise the underlying information to ensure that the information required is presented for the particular crew requirements for their current tasks. For example, an information manager may consider identified SAM positions and types in relation to the underlying terrain, and calculate 'safe' areas to fly. In turn, this 'fused' information could be used to contribute to route costing.

Further, with the provision of more generic graphical displays in the cockpit, capabilities will be introduced to configure and re-configure the presentation of information. For example in situations of possible display failure or malfunction. The EC will therefore need to have knowledge of the cockpit layout and availability of display surface real-estate to support the management of presented information.

#### **4.2 Reliability: Integrity, Fidelity and Quality of Information**

The EC needs to know, and be able to convey, information to the crew about its knowledge of the quality of the information to be presented. If the underlying systems from which the data originates are questionable or malfunctioning, this needs to be able to be relayed to the crew. The reliability of information sources must be conveyed.

The examples above are all examples of qualitative presentation. In the case of the last example, the information can be presented graphically very economically.

#### **4.3 Stability of Information**

The dynamics of the emerging situation may greatly affect the operation of the human-EC team. The noise present in

some information may transfer itself to the displays. If the EC cannot decide, as in the first example, whether a piece of information is relevant or not, confusion may result.

In such 'fuzzy' situations the processing overhead or workload can be very high. Decisions about interpretation of the situation are required of the man machine team, as well as what to do about it. In addition, the processing overhead, both for the human and the EC, associated with generating options can become prohibitive. By working together, the man and machine should be able to make a better assessment of the situation and response options.

It is important that 'fuzzy' information is not presented in such a way as to engender a 'switch off' response by the man. Two types of switch off response might be considered, involving conscious and unconscious but unilateral decisions by the man. The first might occur where the crew decides that the machine must be malfunctioning because of the behaviour of the information presented. The second occurs when the information presented does not fit the situation perceived by the crew; a difficulty to do with belief systems.

As far as possible, information must be displayed in such a way as to present self-evident solutions. Possibly the biggest threat to decision-making time comes from workload associated with instability and uncertainty in information presentation; dithering is potentially fatal; dithering is not 'right-stuff'.

#### **4.4 Completeness and Uncertainty of Information**

The requirement for complete information will be determined by the set of concerns currently being resolved by the crew, including the need for them to monitor the emerging general situation in anticipation of predicted tasks. If the information that can be provided is incomplete, it may be preferable not to use it if its presentation will lead to questions in the crew's mind and possible incorrect interpretation and extrapolation. On the other hand in some cases, incomplete information may be better than none.

**e.g.5:** EC: "I'm still getting intermittent and sketchy tracks about the possible SAM site at (x,y) that I told you about 5 minutes ago."

It must be remembered, however, that complete information is an aim rather than an achievable reality; to some extent there will always be, and always has been, uncertainty.

The design of the display must include a qualitative way to enable the representation of uncertain information. A display would then be able to convey for example:

**e.g.6:** EC: "I am ninety something percent certain that the SAM site somewhere within a radius of 100 meters of (x,y) is a SAM-13."

Where there is uncertainty, mistrust can follow.

#### **4.5 Aircrew Trust**

Although introduced with the best of design intentions, increasing sophistication in a technology can mask functional complexity, for example through degrees of automation. This has often been viewed by crews with apprehension, though they tend to display a lack of understanding of automation, rather than mistrust<sup>[8]</sup>. Further, the impression that automation is not sufficiently capable or knowledgeable may be founded on experiences of ill-considered implementations of automated functions.

The human-EC interface needs to be designed with regard to these issues, or the ability for the EC and human to work as a team in difficult situations will be compromised from the outset. Essentially, the human crew needs to be able to see the right information, at the right time for the task.

In order to preserve situation awareness and minimise any ill effects upon workload, the crew need to be sure that any information that is presented in the cockpit:

- \* Is supporting what the EC is trying to achieve;
- \* Contains sufficient data/information to enable the crew to identify the tasks which have to be performed;
- \* Contains sufficient information and data to allow the crew to perform their tasks.

It is necessary therefore that the interface to the EC contains sufficient accurate information in one form or another for the crew to identify and perform their tasks.

Understandably, aircrew can be suspicious of untried technology and concepts; their views can be prejudiced by previous 'bad' experiences. The potential areas for mistrust can be better understood by involving aircrew in the design process from the inception. It must, however, be borne in mind that where a crew of today may not trust a system due to its immaturity or lack of familiarity, the crew of tomorrow may have been brought up with such concepts, systems and technologies.

Aircrew trust needs to be built through the provision of sufficient information to allow them to understand why the system is doing or saying what it is. Mission support information must be clear, concise and easy to use. This is particularly applicable to automation concepts. [5][6][7][8]

**e.g.7:** EC: "...the probability of mission success can be improved to 90% by fine tuning the current route plan. I have 6 alternative options currently calculated."

#### 4.6 Human Limitations

Basic human capabilities will not change in the future, but what can change is how those capabilities are utilised. This will require careful consideration of the benefits of the technology to support the crew of a manned aircraft and not replace them.

A key factor for the crew interface system is to design an information system which takes account of the attributes of both the human and the machine.

It is very important that an equivalent or at least very similar situation is perceived by both the machine and the man; their individual perceptions of the situation should be coherent, so that they have a common view of the situation on which to base decisions.

For example, difficulties arise due to the ability of the human to build a mental model of a situation, which can bias judgements about an emerging situation to such a degree as to completely block even important changes.[9] A glass half-full presents one positive image, but a glass half-empty presents the same information but in a negative sense.

**e.g.8:** EC: "...the current plan has a 70% chance of success."

...or...

**e.g.9:** EC: "...the current plan has a 30% chance of failure."

#### 5. Conclusions: 'Right-stuff' qualities and design challenges for the human-EC interface

The human-EC system must display 'right-stuff' qualities, so it is essential that EC cockpit interface is designed to make the EC a team member rather than simply a provider of information.

The EC will have to be designed and built with respect to human capabilities. It is important that it is aware of its own shortcomings, and conveys them to the human crew. The converse also applies: the crew must also be aware of their own shortcomings, particularly with regard to bias, and convey them to the EC. Of course, this has to be achieved with respect to total system (man and machine) workload.

The human-EC system must be designed from the outside (or human side) inwards, with respect to, rather than simply in the basis of, its underlying functions.

Requirements capture for the functions and capabilities of the EC, however, presents possibly the greatest design challenge. For example, this paper has considered in particular the four attributes Uncertainty, Probability, Stability & Assumptions. Are there others? Is 'Appropriateness to Mission' a possible contender?

The crew-EC interface must therefore be able to present large amounts of information in a form that enables the crew to maintain their awareness of the dynamically emerging situation by:

- \* Understanding what the interface is telling them;
- \* Providing sufficient information to enable them to identify and perform their task;
- \* Identifying any uncertainty in the data;
- \* Understand what the system is recommending and why;

<sup>3</sup> Refer to OPACITY.

- \* Allowing the crew to use their abilities to best advantage while supporting them in those tasks which they are less capable of performing.

Ways need to be found to present information with respect to its meta-characteristics and qualitative aspects. Where an EC is generating a solution, then the solution and the problem should be presented together in an honest and convincing way. A major systems design factor for the crew interface is the presentation of integrated information, 'image making', so that information is presented in such a manner that the solution is, as far as possible, self-evident.

### Acknowledgements

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# **Tactical Training System for Air Crews**

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**Daimler-Benz Aerospace**

**Sept. 97**

## **1. Summary**

The ground based Tactical Simulator, working in a Dasa Enhanced DIS, standard DIS, or „Stand alone“ with individual training tasks. In all configurations are a high number of intelligent, unmanned, full mission virtual players responsible for a high fidelity Combat Szenario.

These unmanned, full mission virtual players will also be able to communicate. The number of participants include all force packages which are required for realistic training.

Scenario Editing, real-time Scenario Management and Monitoring, presented on a Tactical Display (god eyes view) or a 3D view attachable to each entity, as well as recording and replay is available for Exercise Management.

Simulation of Fighter Controller Working Position is also included.

The tactical training system for air crews was presented for the first time at the ITEC exhibition, Lausanne, 1997, showing an ISDN connection of 2 simulator cockpits, one at Lausanne, one at Ottobrunn.

## **2. Introduction**

Due to the fact that weapon systems get more and more performance, the pilots can no longer fulfill their training with only real flying. The flight hour of the weapon system is very expensive, the use of weapons only allowed in a few special areas. Training together with other pilots in complex scenarios (ComAO) happens not very often, for some pilots never.

On the other hand complexity and performance of the weapon systems is raising rapidly.

To solve this problem the tactical training system for air crews is in development by Dasa.

## **3. Meaning of Tactical Training System**

The tactical training system for air crews is a ground based training simulator with a network, connecting different crews (airborne weapon systems, AWACS, fighter controller station, including air to air weapons, air to ground weapons) into complex training scenarios.

Only those, who have to be trained are real, all others are simulated (virtual players).

The system can be used for education, refresher training, mission rehearsal, learning or developing new tactics, and weapon system ratings.

It is also possible to have autonomous single pilot cockpits, which are powerful enough to run complex scenarios due to the virtual players.

## **4. Advantages of simulator training**

Only trainees who have to be trained are „flying“, other entities are simulated. Extreme manoeuvres can be trained (Head on attack/passes ( $<20^\circ$ ), close combat), if the visual system is appropriately selected.. It is possible to train new tactics with new weapons like in reality, but without risk.

Multi Bogey Environments (whenever required, not only once a year or less), which means a higher number of entities than in

real flight training, totally independent from season, weather and location. Besides the advantage that training effectiveness could be easily evaluated, training costs are drastically reduced.

Network to other existing simulators and/or in future a closed loop with real flights (weapon system simulation in flight) is an option of this system.

## **5. System description**

### **5.1 Network**

The system is connected via standard ISDN telephone lines world wide. Typically 3 - 4 ISDN lines (64kBit/s each) are required from cockpit to cockpit for a scenario of 30-40 entities.

The protocol used is the Dasa enhanced DIS protocol. The system can optionally be driven with DIS or in future under HLA. Dasa also has experience with the German and US connection standards.

The performance of the network allows dynamic data exchange in real time, without visible stepping.

### **5.2 Virtual Players**

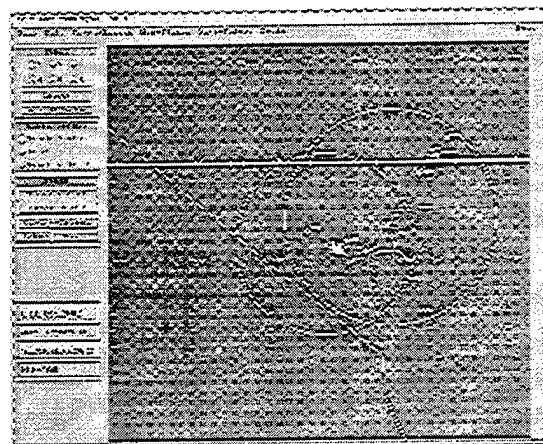
A virtual player is a synthetic combination of pilot and his aircraft/weapon system, with individual, autonomous, intelligent behavior. Each virtual player has its individual simulation task, he decides on his attacks based on the knowledge of the weapon system strategy). Virtual Players can be friends or enemies, from harmless to aggressive. Speech recognition and synthesis, for communication between synthetic and real pilot allows the real pilot to give commands to the simulated wing man, so that he cooperates with the real pilot.

Different weapon systems are available (Euro-fighter, Tornado, MIG 29), others are available on request (Gripen, Mirage, F4,....)

### **5.3 Fighter Controller Station**

This station is the simulation of the working position of the fighter controller. All necessary data links between this station and the simulated and real entities provide the tactical situation to the controller.

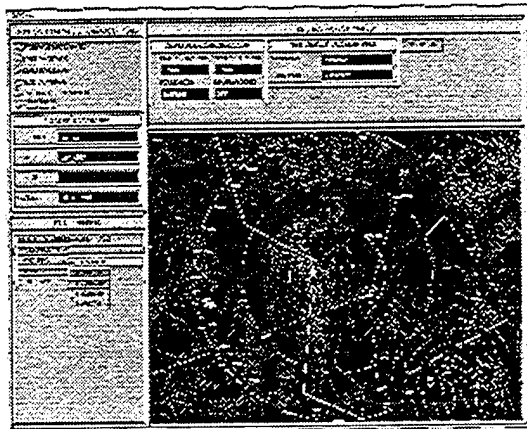
### **5.4 Simulator Control and Mission Preparation (Scenario Manager Station)**



The Real-time Scenario Management and Monitoring is presented on a tactical display (god eyes view), alternatively a 3D view can be attached to each entity.

Tools for scenario editing and mission planning are available, as will be editors for environment such as weather conditions (fog, rain, hail, snow, thunderstorm).

The system also allows simulator control with the functions, start, stop, freeze, continue, record, re-play, malfunction simulation and emergency initialisation



#### 6. Future enhancements

The system will also get links to real aircrafts and those which are using „weapon system simulation in flight“ a future product of Dasa.

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# **COLLABORATIVE INTELLIGENT ASSESSMENT OF AIRCRAFT MECHANICAL SYSTEM FAULTS**

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## **SUMMARY**

This project concerns the development of a collaborative human-electronic capability for management of aircraft mechanical faults. Health and usage monitoring systems (HUMS) have been developed for application in rotorcraft operations to address identification of fault conditions and tracking of system usage relative to component life expectations. HUMS systems employ various sensors (e.g., oil pressure and temperature, torque, vibration) for engines, drive train, and rotors, along with processors to identify critical conditions. The present work addresses the development of alerting information for the aircrew regarding HUMS-identified mechanical faults. Focusing on the Navy's aging fleet of H-46 aircraft, we have conducted an experimental determination of aircrew information needs for fault management. We are developing an intelligent interpretive layer on top of separately provided diagnostic and prognostic algorithms to aid the aircrew in accomplishing fault management functions such as corroboration, impact assessment, and action determination. A draft aiding concept and aircrew interface will be presented. We will also address the critical questions of "When is indicator reliability good enough to present to the aircrew?" and "How can we best design an interface and decision aid to help the aircrew to deal effectively with inherently uncertain warning information?"

## **INTRODUCTION**

Health and usage monitoring systems (HUMS) involve the application of a variety of advanced industrial equipment monitoring technologies to helicopter mechanical systems. HUMS systems have been developed and implemented by several vendors over the past decade in order to provide improved diagnostic data for ground-based maintenance operations (summary reviews of HUMS technology are available in Stevens, Hall, & Smith, 1996; Parry, 1996, Marsh, 1996). The majority of HUMS installations to date have been made by UK and Norwegian operators who provide helicopter ferrying services to North Sea oil platforms. These installations have been made in order to improve flight safety, and have been quite successful in this regard. The U.S. Navy has recently conducted an Air Vehicle Diagnostic Systems (AVDS) program (Chamberlain, 1994) in order to investigate the potential benefits of HUMS technology to improve safety and maintenance in aging rotorcraft fleets (particularly H-53, H-46, and SH-60) and to facilitate the Navy's transition to a paradigm of "condition-based maintenance" (CBM). CBM is intended to replace the current usage-based maintenance policy whereby major maintenance actions and component replacements are scheduled according to recorded aircraft component usage (typically flight hours, operating hours, takeoffs, landings, etc.) as compared to expected component usage life. Since usage-based maintenance policies are necessarily quite conservative, a conversion to a CBM policy

is expected to produce significant savings in maintenance costs along with an improvement in aircraft safety.

Current HUMS systems do an excellent job of monitoring and recording usage data in fine detail so as to enable improvements in usage-based maintenance. However, in the area of health monitoring, current HUMS capabilities are more limited. While many mechanical faults can be reliably identified, many others are quite difficult to diagnose. For health monitoring, interest has focused particularly on the use of vibration sensors (i.e., accelerometers) which are located around key drive-train components. Vibration data are especially important for monitoring gearboxes for which (unlike engines) there are very little other indicator data. A variety of techniques have been developed to analyze and interpret HUMS vibration data. One approach employs higher order (e.g., fourth or sixth moment) feature vectors that are derived from the raw vibration data, and then compared with norms for those feature vectors in order to determine when an anomaly exists. Another recently emerging approach uses neural network algorithms to compare raw or processed vibration data with patterns for known faults, and so achieve diagnoses. Both of these approaches require considerable analytical and subjective judgment on the part of the HUMS expert. In the particularly critical and challenging area of rotorcraft gearboxes, high false alarm rates (in the vicinity of 20% to 40%) are reported for returns of non-faulty gearboxes to the manufacturer.

HUMS technology appears to have considerable potential for alerting the aircrew of in-flight developments of mechanical faults. This situation, however, presents a rather unique and challenging opportunity in human-centered design. While the underlying technology is evolving rapidly and high levels of uncertainty are associated

with many sensor patterns and fault conditions, there are also immediate opportunities to provide valuable lead-time warnings to aircrews of impending catastrophic mechanical failures. While it may be tempting to wait for the HUMS technology to mature before designing an aircrew interface, the potential near-term safety benefit is more compelling. Of course, a thorough cost-benefit analysis must be conducted and an appropriate aircrew interface design must be developed before any HUMS data are presented to the aircrew. The remainder of this paper is concerned with the aircrew interface design process.

## INTERFACE DESIGN

The aircrew interface design problem consists of determining what information to present and how to present it. We will focus mainly on the former of these issues because it is quite difficult and still not fully resolved, and it is logically prerequisite to the latter information presentation issue for which fairly well-established principles and techniques are available.

In order to determine what information should be presented to the aircrew, it is necessary to establish both what information the aircrew needs and wants and also what information can feasibly be generated to satisfy their needs/desires. Since essentially none of the currently generated HUMS outputs are expected to be suitable for aircrew presentation, this process is expected to require iterative refinement. We start by identifying the general types of information that the aircrew needs, then we try to characterize the kinds of information that we think we can generate in the identified categories, then we assess the utility to the aircrew of those specific kinds of information, etc. We assume that all information that might be presented to the aircrew would have to be generated via some kinds of aiding algorithms which would use

the HUMS data as their primary inputs. Such algorithms could vary from extremely simple ones like current chip detector lights which just indicate that some anomaly has been detected, to very sophisticated algorithms which would tell the aircrew precisely what to do to respond optimally to the detected problem.

## INFORMATION REQUIREMENTS

Both analytical and empirical approaches to identification of aircrew information needs are warranted. The analytical approach is needed because it is natural to expect aircrews to be somewhat fixated on types of information with which they are already familiar in current cockpit interfaces, so they may not think to ask for some new types of information that might be very helpful. So we should attempt analytically to identify all potentially relevant types of information. But it is also important to determine what information the aircrew would actually use if it were available because it could be detrimental to present information that they won't use, and it is likely to be quite costly to create many of the algorithms for generating the candidate aiding information.

Our effort to develop a taxonomy of relevant aircrew information needs began with an earlier investigation of the rotorcraft warning-caution-advisory (WCA) design problem (Hicinbothom et al., 1995). We extended the earlier taxonomy to reflect HUMS considerations to produce the taxonomy illustrated in Table 1. This taxonomy includes two types of information - primary and qualifying information. We assume that the aiding information is constructed on top of a layer of HUMS data and information. The aiding information serves to convert the HUMS data outputs into information that addresses the various aircrew information needs. We have envisioned a sort of hierarchy of levels of information progressing from anomaly

identification through diagnosis, prognosis, impact assessment, and leading ultimately to action recommendation. Also in the aiding information layer, but orthogonal to the preceding hierarchy are several types of qualifying information such as corroboration, criticality, urgency, and uncertainty, which can apply to all levels in the hierarchy.

### Primary Information

Anomaly detection and localization  
Diagnosis  
Prognosis  
Root cause determination  
Impact assessment  
Action determination

### Qualifying Information

Corroboration  
Criticality  
Urgency  
Uncertainty  
Precision  
Completeness

**Table 1. Mechanical Fault Alerting Information Taxonomy**

Current HUMS systems provide some data on anomaly identification and diagnosis, but none of this is currently considered suitable to pass directly on to the aircrew. There are ongoing research programs to develop diagnostic and prognostic information from vibration data, but the quality and timing of results in these areas are questionable. Various projections have been made of expected developments over the next five years for the precision and reliability of HUMS diagnostic and prognostic capabilities. While HUMS developers may provide some data suitable for cockpit presentation in the next 5 to 10 years, we must assume that most of the information to be offered to the aircrew will have to be developed through some kind of processing that will operate on top of HUMS. We envision production rule (or expert) systems,

possibly with some model-based components, to be the primary mechanisms for information generation in most of the identified categories. Although it is certainly desirable that the production rules and models be based as much as possible on solid analytical and empirical data, it is expected that the initial formulation of many of the rules will have to be derived by knowledge elicitation from subject matter experts (i.e., by subjective estimation and speculation). In the area of action determination, we expect that this approach is ultimately the only option, since a value decision must be made about the tradeoffs between the various mission outcome possibilities. For action recommendations, we are essentially producing a sort of electronic NATOPS which must naturally incorporate all existing NATOPS and be fully compatible with it. But NATOPS currently only addresses conditions and anomalies that can be identified with current sensors. HUMS greatly expands the universe of cases that must be addressed.

It is also important to note that not all information needs are necessarily event triggered. Some information requests and system interactions may occur at the initiative of the aircrew for various reasons such as the following:

- command of recording events -- Current HUMS systems are memory limited and cannot record data from all sensors continuously, especially from vibration sensors which produce particularly large data volumes. Intermittent recordings are currently triggered by key flight events (e.g., take-off and landing) as well as by cyclic schedules, but these systems also allow the aircrew to trigger recordings based on aircrew concerns about system performance.
- command to perform special analyses -- As sophisticated options for processing and viewing data continue

to develop, we expect the corresponding decisions to be afforded to the aircrew.

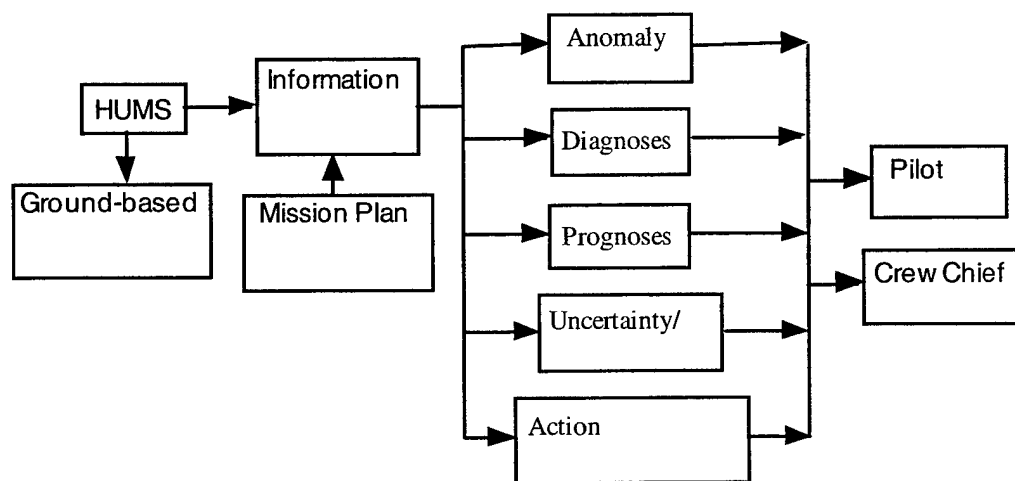
- review of subsystem status data/indicators -- We also expect to provide the aircrew with options to examine both current and historical records of all subsystem status indicators.
- trouble reporting -- Trouble reports could be initiated by the aircrew and recorded so as to facilitate ground crew analysis in conjunction with all corresponding HUMS data.

In order to develop an empirical perspective on aircrew information requirements, a study was conducted with H-46 aircrews at NAS North Island using a motion-base simulator in order to establish baseline performance of aircrews confronted with a variety of mechanical faults and current cockpit instrumentation. Three ten-minute flight segments were conducted by eight variously experienced aircrews (pilot, copilot, and crew chief) in the context of an embassy personnel extraction scenario with one opportunistic search-and-rescue operation. Performance data were collected via videotape, questionnaire, and extensive videotaped debriefs. Objective and subjective data were analyzed to identify areas of attentional focus, types of communications, any evident problems, and types of desired aiding. The results of this study generally supported the above described taxonomy of information needs. Participants reported dividing their attention roughly equally across the categories of display accuracy, diagnosis, prognosis, impact assessment, and action recommendation. However, in classifying recorded voice communications during periods when the malfunction indications were present, we observed many more comments in the category of action recommendation (28%) than in diagnosis (3%) or prognosis (4%), while a substantial number (7%) were concerned with

corroboration of indications. Thus, it is clear that aircrews are concerned with all of the identified categories of information at one time or another. More complete reports of this study are in preparation for presentation at an upcoming conference (Deaton et al., 1997 a & b).

There is also a separate issue of information timing that must be addressed in interface design. The HUMS processor will typically develop a fault analysis over time and initial results may be modified or elaborated as additional data is obtained. It may be possible and appropriate to notify the aircrew of a significant anomaly prior to the development of additional diagnostic and prognostic information. Or, in other cases, it may be more appropriate to withhold presentation of any information until a complete profile, including action recommendations, can be provided. And after a partial or full profile of information is viewed by the aircrew, it may be important to notify them of subsequent changes to aspects of that profile. Clearly, we must develop some means of determining when partial or modified information will be sufficiently relevant and urgent to the aircrew to offset its potentially distracting effects.

Figure 1 illustrates the general concept that we have for aiding the aircrew. A special processor will perform information analysis for the aircrew, taking inputs from available HUMS data as well as other avionics and mission plan data. Information will be provided to the aircrew, via some new Warning-Caution-Advisory (WCA) system interface, in categories such as condition assessment, corroboration, and action recommendations. Our preliminary design calls for initial indications of anomalies to be signaled by a dedicated WCA light (e.g., labeled "DRIVE TRAIN") which then allows the aircrew to request elaboration. The request for elaboration leads to a display of summary information about the anomaly (e.g., symptoms, locus, severity, etc.) which also includes options to branch to further elaborations in the areas of diagnosis, prognosis, action recommendations, and corroboration. We also expect that it may be appropriate to offer somewhat different information to different crewstations, such as to support the distinct roles of the pilot and crew chief in the H-46. A prototype aiding interface is currently being designed and implemented for evaluation in a second study in the H-46 simulator at NAS North Island.



**Figure 1. Aircrew Aiding**

## CONCLUSIONS

Continuing efforts are investigating the types of and constraints on information that can feasibly be generated and presented in each of these categories. Decision and information needs are being identified for each of the crew positions in order to develop interface designs that are tailored to the needs of each crewmember. Issues of crew coordination and training are also being addressed. This work is closely coordinated with ONR-sponsored work on diagnostics and prognostics of mechanical systems and associated condition-based maintenance methods.

At the same time, there are some substantial challenges. The kind of intelligent WCA aid that we would like to develop can be most easily developed in a new aircraft with advanced computers, reconfigurable displays, and a digital data bus. But the need is greatest in the aging rotorcraft fleets, like the H-46 which doesn't offer the desired infrastructure. Also, the underlying HUMS technology and related technologies for diagnosis and prognosis are developing rapidly. There is a temptation to wait for these technologies to mature, but there is also the concern that the need for aiding is now. Thus, for example, we must weigh the high uncertainties we now have in vibration-based prediction of gearbox failures against the catastrophic results of in-flight failures. We must also recognize that information needs probably vary with many other factors which we have yet to investigate.

## ACKNOWLEDGMENTS

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# Considerations on the Certification of an Electronic Crewmember

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## SUMMARY

Research on and development of an electronic crewmember (EC) has matured to allow a transition from the scientific world to practical applications in the near future. With this transition, the implementation in a real world environment reveals new problems beyond the successful application of artificial intelligence technology. At the end of the day, the electronic crewmember has to be certified.

This paper considers certification issues of the EC. Starting point is the definition of two generic EC models and their interaction with the on-board environment. Within this text, the first of these models is called the EC as adviser. The second one comprises the role of a supervisory controller. Although a real EC implementation will probably not match one of these roles exactly, this distinction served well during the generation of this paper and may also assist the reader to become sensitive for the criticality of electronic crewmember functions.

Next, safety concerns regarding the EC are discussed. From a common understanding of the applicable criticality criteria, safety relevant features of both EC models are derived. The analysis shows that the safety impact of the EC is mainly related to human factors, especially the perception of the electronic crewmember by the human colleagues.

Detailed techniques to verify and validate the implementation of expert systems and neural networks are not discussed due to the limited experience of the author with artificial intelligence. But what is shown is a route to certification based on the qualification and certification experience with safety critical systems, in particular flight control systems (FCS).

To get an initial understanding how an EC may be certified a comparison technique is chosen. EC design features imposed by the EC models and the

safety concerns from above are compared with equivalent FCS design characteristics. Finally, verification and validation methods that may be suitable in the EC certification process are derived from the equivalent methods used in FCS certification.

## 1. INTRODUCTION

Automation of aircraft functions has a long history. Around 1930 research on autopilots had achieved a maturity that allowed their implementation in production aircraft [2]. This was the first shift to change the pilot's role from the active flight path controller to a supervisory role. The reasons for the introduction of autopilots might have been similar to those from which modern flight decks have emerged:

- automation of functions that an automatic controller can perform more precisely
- introduction of functions that a pilot is unable to perform
- pilot's workload reduction that enables him to concentrate on other tasks

As a result a more reliable and safer service was promised for commercial transport airplanes while higher mission accomplishment rates were an additional driving factor for military aircraft. However, automation generates safety threats by itself:

- Implementation faults have led to accidents.
- The equipment by which the automation functions were implemented failed and created hazards.
- Specified functionality occasionally did not meet the original intentions and created catastrophic aircraft states.

Thoroughly performed design, implementation and verification of equipment functions are the means for protection against implementation faults. Sound procedures, checklists and independent

verification are the proven methods commonly used.

To mitigate possible effects of equipment failure, warning annunciations to the pilot provide the necessary situational awareness. A direct relation between annunciation and required pilot's action allowed hazard recovery even when immediate action is required. To prolong the reaction time for successful recovery, measures like trim actuators with limited maximum travel speed are commonly used. Or, if this is not feasible as it is for stability augmentation systems, the authority of the automatic mode is only a small fraction of the full travel range to limit the maximum failure transient.

In cases where the pilot is not able to counteract the failure transient, fail-safe devices were invented. Fail-safe techniques have been the first step to implement similar and dissimilar redundancy. The redundant means are used to assess the outputs of the automatic controller for validity. Thus, maximum failure transients are limited automatically to an extent that the pilot can perform safe recovery without exceptional skills.

For essential equipment for which uninterrupted performance is required like digital flight control systems, fail-safe characteristics are not sufficient. Instead, fail-operativeness to the probability level specified for safety is mandatory. Sophisticated redundancy management techniques are the basis to fulfil fail-operative requirements.

Today, aircraft systems have the tendency to be rather complex, especially when digital computers comprise the major portion of the functionality. This challenges design and verification skills. Up to now, no sound techniques are available to prove all presumptions and intentions sufficiently in addition to the verification of the requirements written in a system specification. This is a source of error that can reduce system safety dramatically due to malfunctions of single systems and even more when the interaction of several systems is considered.

The pilot has to cope with these complex systems in normal operating modes as well as with remote hazardous failure modes. The type of system management required has shifted from fixed and straight recovery procedures to recovery processes that need not only immediate action, but also an assessment of complex system states and prioritization of tasks.

Because humans are less suited for the latter, electronic crew members are promising means for

pilots' assistance. However, the electronic crewmember by itself is a technical system and is prone to errors during all life cycle phases like other systems of similar complexity.

## 2. SYSTEM ARCHITECTURE

### 2.1 The Electronic Crew Member as Adviser

Figure 1 shows a functional interface diagram of the pilot, the off-board environment, the aircraft, the aircraft systems and the EC in an advisory role.

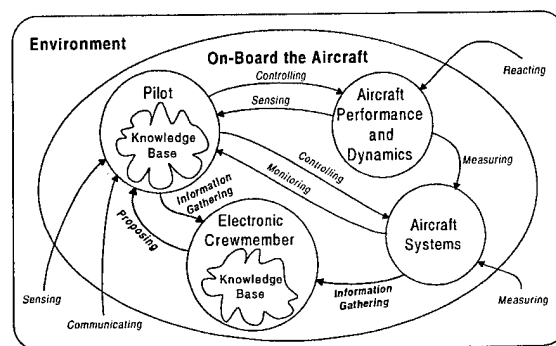


Fig. 1: The Electronic Crewmember as Adviser.

The pilot interacts with the off-aircraft environment by visual cues. Furthermore, he is communicating with air traffic control or tactical control centers. With respect to the aircraft performance and dynamics he also is sensing, e. g. using his inertial and tactile senses as well as the flight displays. Regarding the aircraft systems, he has a monitoring role as well. Let us define monitoring as an integrity assessment of the aircraft systems. The information provided by these means enables the pilot to perform his role as a supervisory controller of the aircraft performance and dynamics states. He also controls the aircraft systems by mode selection.

The electronic crewmember in an advisory role does not challenge the pilot as supervisory controller. Instead the electronic crewmember may have the ability to alleviate concerns in two major areas regarding cockpit automation as stated in [1]:

- Pilot understanding of the automation, its capabilities, behavior, modes of operation, and procedures for use, and
- Differing pilot decisions about the appropriate automation level to use (if any) in normal and non-normal circumstances.

For the assessment of the actual situation the EC gathers information from the aircraft systems and the pilot's behaviour. The correctness of the information is not questioned by the EC. From his knowledge base that is naturally different from the pilot's knowledge base conclusions are derived regarding status accounting and prioritisation of tasks. The pilot is free to follow the EC's proposals or to reject it.

With respect to integrity and safety the advantages of the electronic crewmember as adviser lie in the following areas:

- The EC does not interfere with the redundancy management of the aircraft systems. This makes design and qualification easier because failure modes of the aircraft systems that go beyond defined normal and abnormal operating modes have not to be considered.
- The pilot cannot always be sure that the EC is right with his proposals. That may limit the reliance on this advice. Hence the safety impact may be limited. From flight tests with CASSY [4] some indications are available that pilots may be able to cope with such kind of crew assistant.

However, the mentioned advantages may ease qualification and certification, but there are some safety risks associated with the advisory role:

- Regarding the EC's interface with the aircraft systems, masking of hazardous states by the aircraft systems may become critical. The masking problem is typical for automatic control loops. When a failure occurs the control loop compensates for the failure transients up to its authority limits. When the authority limit is reached no further compensation is possible, the aircraft state is far from equilibrium, and large failure transients may lead to hazardous situations [1]. To what extent the EC as adviser is contributing or mitigating failure masking has to be analyzed for each particular EC function.
- In [4] it is reported that discrepancies between pilots and CASSY are caused by pilot error or by machine error. Both figures are in the percent range. As long as pilot machine errors are not remote pilot's reliance on the EC may be limited. Because this assessment process takes time, an EC of this kind is unable to assist the pilot in cases when immediate action is required. However, it can be expected that the EC will be improved. Thus machine error probability will be order of magnitudes smaller than pilot error probability. A role change to the EC as supervisory controller may be imposed.

## 2.2 The Electronic Crew Member as Supervisory Controller

Figure 2 shows the EC as supervisory controller. The figure is only slightly different from figure 1. Therefore, only the differences and their consequences are discussed.

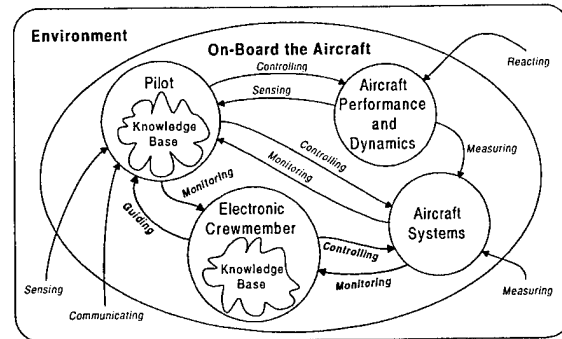


Fig. 2: The Electronic Crewmember as Supervisory Controller.

In this role the EC does not only gather information from the pilot and the aircraft systems, but performs also a monitoring function. This role requires some sort of meta knowledge that enables the EC to give control inputs to the aircraft systems especially for mode control and to guide the pilot to perform particular actions in a certain sequence.

Theoretically, the EC as supervisory controller might be a powerful function with a high potential for flight safety enhancements. However, it is questionable if such a system can be built and even more if it can be certified.

The safety classification of the monitoring function has to be at least the highest classification of the observed aircraft systems. Because the complexity is the major problem for aircraft system design it is not reasonable to cure this problem with even more complexity.

In very general terms, failures can be categorized as expected and unexpected. Expected failures are those considered during development, e. g. during analysis and design or during the verification process. Practical experience has demonstrated that the probability of expected hardware failures is less than calculated because they are mitigated by appropriate means during the design phase. Failure modes not considered have the highest potential to bring reliability down.

For non-hardware of any kind similar rules apply. In [3] many well known catastrophic accidents with technical systems are analyzed demonstrating that unexpected chains of events are the most likely cause for hazards of complex technical systems. Another indication is the fact that in software engineering the number of analysis and design errors is double as high as the number of coding errors [5]. With increasing maturity of coding standards it can be expected that the ratio gets even worse. Most of the analysis and design errors are usually detected during the verification and validation process. However, the most remote errors may not be identified during development and may have the highest hazard potential in service.

One significant result from these considerations is that the verification and validation problem of complex systems is only slightly dependent of the design philosophy, may conventional control laws or may artificial intelligence techniques be used. However, a well structured functional architecture and a more linear behaviour can be better verified than unstructured and extremely nonlinear functions.

The functional interface between the pilot and EC is reflecting the competition between both supervisory controllers. On one hand, the concerns on possible pilot's overconfidence on the EC apply as mentioned above. On the other hand, the EC lacks the flexibility of the human pilot. Therefore, the role of the supervisory controller should always stay with the pilot and should not be shifted to the EC.

Therefore, the EC as supervisory controller is not considered any further in this paper.

However, after all these safety concerns the conclusion is not that electronic crewmembers should be better not implemented. What should be clear is that safety respectively survivability in some military applications is likely an issue for ECs.

### 3. ROUTE TO CERTIFICATION

To propose a route to certification for an EC the development tasks have to be defined in the first step. In this paper the engineering tasks are deduced from the development steps that have to be performed for a FCS by analogy.

In the second step, the commonly used verification methods of the FCS development results of each engineering task are briefly described. By analogy

again, these verification methods are traced to the EC verification process. In some cases appropriate qualification methods can be easily derived by this comparison technique. In other areas further research on suitable verification methods is required. The results presented in this paper are preliminary. Best usage is to consider them as a starting point for further discussion.

For both systems the engineering areas of human factors, system functionality and equipment have to be considered.

#### 3.1 Human Factors

EC as well as FCS have to follow human centered design principles. Therefore, the suitability for service has to be finally assessed by the users. For FCS, pilot assessment campaigns are repeatedly performed during the development phase. Starting with handling qualities simulation in an early stage pilots are involved in the evaluation of basic functions and their integration to the complete FCS. Cooper-Harper rating is the assessment method widely used for achieving comparable results. For flight clearance, the manoeuvres flown in the simulator exercise the actual manoeuvres of the particular test flight. During flight testing the final assessments are made.

This test method is directly traceable to the EC. For the EC handling qualities are related to the selection, prioritisation and presentation of the EC's advice. However, a tailored rating scheme should be used. It is understood that various rating methods are available. It is important for the EC community to harmonize the different assessment philosophies. A common state of the art procedure should be established that can be used in the certification process.

For other ergonomic FCS design features related to FCS inceptors, indications and mode selection design standard and common practices provide the necessary guidance. Compliance with standards is therefore a prerequisite for certification unless good reasons exists for deviating from these standards and are accepted by the pilots. This is quite often the case for new military aircraft that provide new or enhanced functionality. Usually hand on throttle and stick concepts (HOTAS) are common practice for military aircraft.

Because the information flow from the EC to the pilot is already covered by the handling quality assessment the remaining ergonomic issues are related to the information gathering activity of the EC. For design of this interface further research is

still required to define appropriate means that perform their function reliable in the operational environment. It can be expected that design guidelines will be established together with a particular technology. It is recommended that pilots are involved early in this process.

### 3.2 System Functionality

The verification of FCS functionality covers analytic flying qualities, control law engineering and graceful degradation.

Over the years experience has been gained that good or excellent handling qualities are traceable to certain characteristics of the non-human part of the flight control loop. Hence analytic flying qualities criteria are the starting point for control law generation. With updated aircraft performance and aerodynamic data the control laws are refined during development.

It is pretty clear that the underlying models (e. g. differential equations) for FCS control law design are different from the cognitive models of the EC. Nevertheless, something may be learned from the verification methods used for control law evaluation.

The flight envelope expansion of modern fighter aircraft makes it impossible to use a single set of linear differential equations for modelling aircraft dynamics. Instead most parameters are functions of altitude, mach number and angle of attack. The steps usually chosen to validate the control law comprises the following steps:

- Stationary manoeuvre performance is analysed first for all relevant points of the flight envelope.
- Next, small amplitude disturbances and control inputs are simulated to evaluate the dynamics around certain equilibrium points. The simulation results can be validated against linear differential equations that are valid for the particular equilibrium point.
- In the last step gross manoeuvring is exercised, to monitor the performance of the full non-linear system.

The features of the EC equivalent to analytic flying qualities and control law engineering are the control strategy and the outcome of the knowledge base engineering process. From an outside view the EC can still be considered as a hopefully deterministic non-linear process. To verify the EC's functionality a similar stepped approach may be chosen:

- Initially, static inputs are provided to prove the validity of the static recommendations.
- In the next step small variations of single and multiple inputs may be exercised. It is expected that the advice given by the EC is changing also only slightly.
- Next, dynamic variations should be performed.
- Finally, stress testing with a high workload on the EC in extremely remote operational scenarios should be performed.

Graceful degradation is a very important issue of digital flight control systems for aircraft with relaxed or without stability. Graceful degradation simply requires that the system should not rapidly change the functional performance level in case of failures. Because with full operational performance pilot's situational awareness regarding the FCS may be limited due to other sophisticated tasks that are required for mission success. Pilot reaction time increases and failure transients should be still manageable.

Considering the situational awareness problems with modern flight decks in civil transport aircraft, graceful degradation has a wider impact than on FCS only. Because an EC will lead to less pilot workload it is not guaranteed that an EC will enhance situational awareness. Prolonged pilot reaction times together with failure masking may lead to hazardous situations.

The problem with graceful degradation requirements is the impact on the complete hardware and software architecture. However, developers are forced to mitigate hazards identified in the system safety process in a consistent manner.

Verification of graceful degradation requirements is usually performed by design assessments. The compliance with these requirements is further investigated during integration testing on all levels.

### 3.3 Equipment

In most instances a FCS comprises all equipment necessary to perform safety critical functions because FCS has together with engine control systems and armament control systems the highest criticality of all aircraft systems. The EC instead is not a stand alone system. The equipment used for information gathering from the pilot may be part of an EC system, but the EC relies heavily on the data provided by other aircraft systems designed with respect to varying integrity levels.

The engineering tasks related to equipment development comprise hardware and software development and several supporting processes. The most important one considers safety and is highly related to the redundancy management features of the particular system.

Hardware development covers sensors, computers and actuator hardware. For FCS as well as for EC well established methods are applicable covering design assessments, environmental qualification and endurance testing.

Software design and verification has usually to be performed according to established software standards. However, software engineering is a rather young engineering discipline with some generally unsolved substantial shortfalls in the verification process, especially if systems are complex what they usually are. In the last decade low level implementation problems were mainly solved by improved development tools and procedures. On this level complexity should not be an issue.

It can be assumed that verification of EC software will benefit from the general achievements or that new methods required can be invented with reasonable effort.

Verification of the software and system integration process has to be considered in more depth because unexpected software errors are mainly introduced on higher integration levels. Because all possible test cases cannot be performed, the system architecture should separate functions and minimize the interfaces between them as far as possible. Then a bottom-up integration test approach shall be applied. Test cases should cover normal operation tests, timing tests and robustness tests. Mode changes should be verified thoroughly.

For the EC special emphasis is required to validity of the data received from other aircraft systems. Integrity shortfalls of single aircraft systems have an impact on the EC integrity especially when invalid data is labeled as valid.

To minimize the effect a system safety programme should be performed to trace possible hazards and to mitigate them by appropriate means, usually by redundancy management considerations. Redundancy may also be required due to the graceful degradation requirement.

#### 4. CONCLUSIONS

In this paper two EC models were discussed. While the introduction of an EC as supervisory controller in an inhabited aircraft cannot be recommended today, the EC as adviser promises functional enhancements that have a potential for increased safety and survivability. However, the integrity of the EC cannot be better than of the input data provided by other aircraft systems and a nearly perfect EC may be a source of pilot overconfidence in the given advice.

A route to certification was derived from common certification practice with FCS. This initial analysis has revealed no general and unsolvable certification problems. However, many issues have to be solved in particular for the certification of an EC.

Finally, it has to be noted that the EC is sensitive to unexpected failures like other systems. These unexpected failures are mainly caused by the slight differences of intentions and written requirements which can be usually observed in case of complex systems. Furthermore, the EC provides no means to solve this problem for other aircraft systems.

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# Certification of the EC / Aircrew Team - a Cognitive Control Loop

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## ABSTRACT

Certification can be defined as the

"Procedure by which a third party gives written assurance that a product, process or service conforms to specified requirements."

(ISO/IEC Guide 2).

There are no existing standards to allow the certification of avionics resident Knowledge Based Systems (KBS), as may be a technical part of the future aircraft Electronic Crewman (EC), and none yet devised for an EC. It is argued that the certification of KBS technology itself requires additional considerations to those already applied through software engineering standards. With KBS there are additional Verification and Validation (V&V) considerations that must be placed on the knowledge base, the KBS model, and the output advice. In addition, a Man Machine System (MMS) that includes an EC will involve a cognitive control loop. This loop exists because the EC and the aircrew will be developed as a team sharing flight and mission related cognition. Thus the homeostasis of the cognitive control loop relies on a sharing of cognitive aspects of EC / operator teaming including the team's complementary application of pertinent mission knowledge, flight information, operational expertise, and situational awareness. It is argued that such a loop would have to be open to examination, and reliably perform its required control functions, to gain acceptance for its adoption and certification for airborne use. Related issues to the problem area are discussed.

## BACKGROUND

The difficulties involved with the certification of a system vary with the system application and the complexity of its constituent parts (for example, its software, hardware, and liveware). The certification of software based avionics is based on well-established V&V principles and developing methods such as employed by software Static Code Analysis. Verification is the process of evaluating a system or component to determine whether the products of a given development phase satisfy the conditions imposed at the start of the phase (Def Stan 00-55). In contrast, Validation is the evaluation process that ensures that the developed product is compliant to the given product requirements.

Hardware principles are also well established. System acceptance principles are less well established but are based on specified system performance criteria and a regime of testing, evaluation and acceptance. Aircrew certification is in the form of an endorsement of their reliability and expertise. This endorsement process includes an appraisal of the standard of aircrew ab initio & continuation training, and frequent in-flight and simulator based evaluations of their

level of competence with relation to the conduct of safe flight and associated aircrew tasks.

Current UK Military certification of Safety Critical Systems in aircraft involves satisfaction of many requirements, much of these contained in the UK software engineering Defence Standard (Def Stan) 00-55, Def Stan 00-56, & Def Stan 00-58. Applied with less rigour, these standards can also be applied to non-safety critical systems such as mission critical systems. The focus for the certification of a mission critical system is the criticality of that system performance to mission effectiveness. In contrast, in certifying a safety critical system, the criticality of that system to the safe performance of the mission should be the prime consideration.

However, none of the existing standards specifically addresses the certification of Knowledge Based Systems, or an EC, or an EC based mission or safety critical system, as might be part of the future aircraft Man-Machine System (MMS). Such systems could be associated with the management and control in a fighter cockpit or with the tactical conduct of a mission in the rear crew area of a multi crew aircraft.

Current avionics systems provide various forms of feedback to the aircrew on system performance, its operating status, and aircraft progress within the flying environment. Control of the aircraft systems is generally either automatic under the supervision of the aircrew, or actioned directly by the aircrew. Engineered systems and aircrew manifest a strict partition in system control functions. However, if control feedback changes its form from that of information to that of advice, then system control will be truly system based and shared between the human and the engineered components of the system. Note that this does not mean that the responsibility for the direction of the system is a system function. Responsibility for system direction should remain within the remit of designated aircrew. However, the control of the system to maintain its direction towards planned system goals becomes the control task of a 'Joint Cognitive System' (Hollnagel & Woods, 1984).

Control theory has long been capable of specifying the dynamic control changes required to direct the necessary machine processes to adapt to changes caused by environmental influences or operator inputs to the machine processes. The seminal works by Weiner (1948) and Ashby (1956) on cybernetics introduced the idea of homeostasis in MMS; adaptive control to maintain a stable and required man-machine system state. However, a MMS that includes an EC will involve a control loop whose homeostasis relies on a sharing of cognitive aspects of EC / operator teaming including the team application of pertinent knowledge, expertise, and situation awareness. Such a loop would have to

reliably perform its required control functions to gain acceptance for its adoption or certification: in other words it must do what it is required to do in a variety of situations and in a sufficiently consistent manner to allow confidence in its acceptance.

Further to this discussion, EC related certification should involve V&V examination of at least four separate processes as associated with:

- EC Model certification;
- Certification of the elicited inputs for the EC;
- EC software certification
- MMS System certification.

The first process can arguably be catered for by logical model generation, including tests for validity and for good result replication. The second process would probably require iterative examination of the knowledge, rule (possibly skill) inputs by several appointed and independent assessors, these assessors having a roles similar to those of present day flight crew assessors. The certification through such a process might result in an agreed rating of the EC depending on its performance and maturity. The third and last processes can be catered for by current certification methods -, does the system reliably and validly meet the requirements of the system specification and allow verification of its quality of build? The last process would encompass the results of the previous processes and might also include an assessment of the competence level of the EC manufacturer as suggested by the current Software Engineering Institute (SEI) 1996 Capability Maturity Model (CMM).

To be operationally effective an EC would have to be continually developed (trained). Changes in any one of the first three of the above processes could affect the veracity of the whole EC / operator team -, as might a change of operator. Therefore, the examination of all of the above processes would need to be iterative and the findings applied as refinements to the MMS throughout the EC life cycle. The amount of iteration and refinement allowed by the certification process would have to be carefully considered and administered (for example the problems of configuration control).

Further, it is to be expected that eventually with EC design, since an operator's cognitive control performance varies between and during a flight and also with changing flight conditions, that the EC could adapt to changes in its environment. The EC would have to be aware of such changes and be able to adapt its teaming assistance

accordingly. Thus, the concept of a future adaptive controller must cover a team interaction policy as well as a man-machine system control policy (Hollnagel, 1995) -, and all this detail has to be unambiguously specified during concept and development prior to the EC build and eventual certification.

Note that the EC consideration in this article refers to a 'one-to-one' pairing between a single member of aircrew and a single EC. The certified use of any EC technology within a multi crewed aircraft environment would present additional unique and complex teaming problems.

## PURPOSE

The remainder of the paper will amplify some of the arguments and issues related to the problems of the certification of a MMS cognitive control loop. This amplification considering the performance requirements of the whole EC / operator team, and the affects on the processes of control of diverse, hostile, and uncertain environments (MacLeod & Wells, 1997).

In addition, the need for a method supporting the specification of system cognitive functions will be briefly visited to introduce an issue that it is argued must be addressed to allow EC certification within a system (MacLeod & Scaife, 1997). System cognitive control relies on an understanding of what system functionality is necessary to support that level of system control required to support system direction towards the fulfillment of system goals and the effective satisfaction of system purpose.

Figure One represents a model of process control for a military aircraft system. Examination of the figure shows that the problem space of EC work would have to reside to a greater or lesser extent across three areas of the model, namely:

- Sensor control;
- Cognitive control;
- Equipment, aircraft, & weapons control.

With an MMS including an EC, situational awareness must be shared through some form of dynamic apportionment within the team (MacLeod, Taylor, Davies, 1995). Further, the model deals with uncertainty as might exist in a hostile military environment and indicates how that uncertainty may be caused and its affects ameliorated depending on the applied level of aircrew expertise. Thus both expertise and planning / tasking mediate the cognitive loop appraising the environment.





### The utility of existing standards and methods

Existing standards and methods are designed to be applied to current Software Engineering (SE) practices (for example Def Stan 00-55, ESA PSS-05) and Systems Design practices (for example IEE P1220, ARP 4754). Current software standards are naturally products of their time and would all require tailoring to fit the specific problem area of future EC certification

Conventional SE recognizes the usefulness of both formal and informal methods. For example, informal high level specification can be performed by structural analysis method such as Yourdon; formal methods such as VDM allow the detailed specification of the software functionality; and results can be evaluated as prototypes by executable specifications such as PAISley. In contrast, though it is early days yet, it is likely that effective SE methods applicable to KBS will be a mixture of formal and informal methods such as MIKE (Angele, Fensel, Landes, Neubert, & Studer, 1993).

Showing their recent maturity, system engineering models emphasize early requirements capture and an iterative approach to the specification of system functions, the separate consideration of logical and physical models, traceability of requirements, iteration, trade-off studies, and the need for careful control over the overall engineering process. A simple system-engineering model is shown in Figure Two overleaf.

The traceability, control and iterative nature of the systems engineering design instinctively seems to be more applicable to the development of the future EC, this extrapolating from current considerations on KBS issues. However, the strong emphasis on the early capture of system requirements might require some amelioration with

respect to the EC component of the overall MMS. Further, the spectrum of EC consideration (see Figure One) should require that the specification of the system, and the EC, contain not only a logical consideration on the engineered system but also on the cognitive requirements of that system. For example requirements on understanding, anticipation, control, situation analysis, supervision - to name but a few (MacLeod et al, op cit.). Importantly, cognitive requirements are necessary for the build of an EC as part of the necessary specification of its support role to the direction and control of a military aircraft system. This role will require that complementary advice to the aircrew includes suitable elements of anticipation and prediction on system performance under environmental uncertainty.

Existing standards and methods can give much guidance to the route needed to satisfy future EC V&V requirements, requirements that will inevitably be tailored to meet the needs of the EC certification process. All of the above arguments are affected by the complexity of the issues affecting the V&V process associated with an EC. These issues will be discussed in the next section.

### The complexity and number of issues involved in EC system certification

There are many interrelated issues involved in the certification of an EC. The seeming complexity of EC related issues, compared to those applicable to current engineered systems, is probably as much related to the relative newness and lack of understanding of the subject area as to their actual complexity. The number of issues that could be discussed is indicated by the contents of the list in the Issues Section above. Considering that list as representative of the issues to be addressed, these listed issues will be discussed in the following paragraphs.

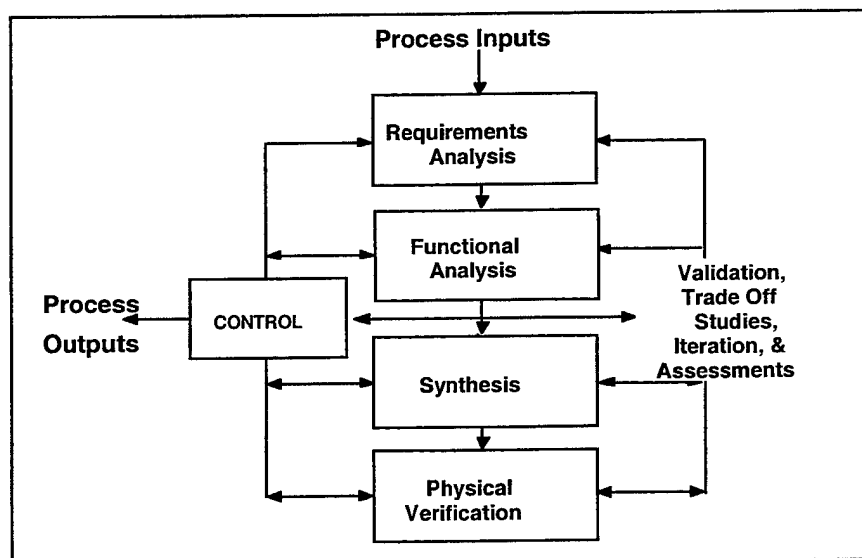


Figure 2: Example of a generic SE process model (after IEE P1220)

### *Safety*

The Safety Issues in the design of an EC will depend on the implementation methods chosen for the EC, the form of criticality of the system, and the maturity of the safety analysis techniques used in verification and to assess the system for certification. It is suggested that whatever integral KBS system is used, and depending on the form of the other components incorporated into the EC sub system, the EC will have to be seen to be designed as 'fit-for-purpose' with the use of generic components (for example, COTS) being carefully argued as being context independent or dependent depending on their purpose in the EC.

### *Form of criticality*

The importance of the form of criticality has already been stressed. Safety issues will vary with the form of criticality as will their examination. For example, the safety analysis techniques applied for a Safety Critical System would have to be applied with greater rigour, or allow greater confidence to be placed on their results, than similar techniques applied to a Mission Critical System.

### *Maturity of model*

Maturity of the EC the model can be expressed in terms of time in service, proven usefulness and usability, and reliability in performance. Also important is consideration on the maturity of the technology and techniques used to specify and develop the EC. The more mature the model the easier should be the certification process.

### *Methodology*

Issues of methodology are closely associated with the issues of criticality and maturity. Certification will be difficult without validated methods of assessing the build, knowledge, and advice / competence of the EC. These methods will have to be both qualitative and quantitative in nature. With the qualitative methods, argued as appropriate to assessing the HOW and WHY aspects of work knowledge and advice, there will need to be developments in the assessment of the accuracy and validity of results (for example, method such as 'triangulation' - Richardson, 1996).

### *Life cycle*

There are many definitions of a design life cycle, these varying between professions and applications. Sufficient to say that the software engineering consideration of a system development life cycle span is generally shorter than that proposed by systems engineering, which again is generally shorter than that envisaged by the customer of the system. Life cycle considerations, and the frequency of system upgrades, have implications with relation to considerations on the maturity of the EC and will be discussed in greater detail when considering the Maintenance and Refinement of the EC.

### *V&V methods*

V & V methods for an EC will be difficult to apply because of the diverse technological developments that are liable to be involved in its build (for example, neural nets, KBS, relational data bases, automatic communications). Existing

approaches to KBS V&V lack maturity and are too narrow in scope to meet current certification requirements for airborne avionics systems. The KBS V&V approaches tend to focus on the KBS and ignore the real world airborne issues associated with the use of KBS within an aircraft system, issues that must be considered by the certification process. Current SE practices and methods are available to allow software build to meet the challenges of the existing certification processes. KBS and the EC should consider the best practices existing with the current SE profession, including the 'Old Physical Model', that are applicable to their certification process. Further, consideration of the old model should allow the existing expectations of the certification community to be understood in order that the similarities and differences of the new application of technology, through the EC, can be argued and understood by that community. It is suggested that it is only by this route that the certification community can be convinced that processes can be set in place allowing the certification of airborne KBS / EC.

### *Testing*

System testing requires a good knowledge of what is to be tested, how it is to be tested, and the expected system performance. Models of the system and of its constituent parts can depict such knowledge. Progressive testing of a system is the feed to the V&V process that gives assurance that the system design is progressing as planned and assists in de-risking the design by highlighting inherent problems. A system model is traditionally rooted in system requirements. A requirements specification is argued to be just as essential for an EC as for any other engineered system. However, the associated functional specification of the EC will have to be constructed iteratively in the light of the designers' increased understanding of problems and processes associated with the EC work area. Indeed, many of the EC functions will be evolve from progressive testing. Therefore, the waterfall model is not appropriate as a more iterative approach will be needed to EC design, and probably to the design of most future complex systems. Aspects of the Systems Engineering model (see Figure 2) are more appropriate than the standard waterfall model.

However, it is probable that the EC development model will be different from the systems engineering model but will have to interlace with that model at different stages of the overall system design process. Testing of the EC must rely on a good knowledge of the anticipated utility of the models associated with the build, models that will be refined in the light of test results and design experience. Integration of sub systems such as an EC into the overall system architecture will be important. The models of real time sub systems and systems must be compatible and their development plans must be carefully integrated. Therefore, for an EC these models should encompass as a minimum:

- An EC Model;
- A model of elicited knowledge (Use of this model will vary depending on the needs of the technology. For example there are differences in the use of knowledge between rule and case based KBS);
- An EC / Aircrew teaming model;

- An aircraft system architecture model;
- An aircraft system function model;
- An aircraft system performance model.

#### *Maintenance & refinement*

A simple definition of a design life cycle is 'from birth to death' of the system. However, it can be argued that such a definition is incorrect as even when a system is 'retired' the lessons learnt from that system will affect the birth of another -, the model is in reality one approaching perpetual motion. It is suggested that whatever technology and disciplines support the construction of an EC, the continuous nature of system maintenance and refinement that an EC will need, to promote and maintain its efficiency, fits it better into the a 'perpetual motion' form of life cycle. To maintain such momentum requires that testing is conducted that is associated with effective V&V methods and an engineering model of the system that allows progressive refinement and an associated evolving EC system maturity.

#### **The overall system architecture in which the EC resides**

Current KBS concepts are developed on systems in 'stand-alone' environments that are divorced from the complexities of aircraft systems (though simulations of some of such systems may be used to assist the development). In reality, the future KBS and EC will have to exist within a real-time distributed system of some form. To be accepted by the crew the EC must be situationally aware and be useful if not invaluable. To be useful as a surrogate crewman the EC contributions to the work of the man-machine team must be timely, appropriate, and the quality of advice must be consistent. Timeliness is a serious inherent problem that has not been fully addressed by current KBS developments but that must be resolved with relation to in-service use of KBS and the future EC. In current real-time systems correct answers must be produced within strict time constraints. EC advice will have different requirements, with relation to time constraints and output accuracies / quality, than a system that merely calculates and presents feedback data or information. Nevertheless, certification processes will almost certainly demand that the bounds or tolerances of the EC performance are known and that these bounds do not detract from overall system performance or its safe use. Possibly two KBS will be needed as a check on one another; number one producing the best solution possible within the allowed time frame and the other producing an 'optimum' solution. This optimum solution may or may not fit the required time frame, and might only be made available to the operator on request, but could be

engineered as a check on the performance quality of the number one KBS.

To conclude the discussion in this section, Table One overleaf lists the main issues raised by the Def Stan 00-55 with relation to the acceptance of avionics based Safety Critical Software. With less rigour in application these practices can also be applied to the certification of Mission Critical Software. The table considers these issues against the development of a typical stand-alone KBS development to illustrate the differences between the current practices on SE certification and the development practices for KBS. Please note that these differences are presented solely to give an illustration of the possible extent of the development of EC design practices that are needed to meet future SE practices. In reality, the particular differences between the needed EC practices to achieve certification, and current SE practices, will be dictated by the nature of the technologies used for the EC build and could be very different to those presented in Table One.

#### **CONCLUSION**

There is a great deal of practical consideration that needs to be placed on the certification of the EC. This consideration starting from the considerations of present V&V practices for KBS, the gap between KBS V&V and current SE and system certification requirements, and continuing to the much greater issues involved with the certification of an EC.

The current requirements for avionics and aircraft certification are well known. Starting from the baseline of the current requirements, we need to practically complement and supplement these requirements to meet the certification case for the EC and its supporting technologies. It is important that a practical engineering emphasis is maintained, drawing from academic and research studies in the field, as the EC certification process will probably be similar to those employed currently. Current certification processes require more than a method of conducting the certification, the process also requires real time system operation, system evaluation, and the production of sufficient quality evidence to support the independent certification of the subject system.

We are emerging from an era where the overall emphasis was on developing technology and methods to suite the concept of the EC. This work must not cease. However, it is time to change some of the emphasis of the work towards a better consideration on the practical real time applications of an EC and its quality introduction into the operational world as part of avionics systems. This task is as challenging as any that have gone before.

Def Stan 00-55 Section	Covered by SE Practices	Not Covered By KBS
<b>Safety Management</b>		x
<b>Roles and Responsibilities</b>	✓	
<b>Planning &amp; Management Processes</b>	✓	
Quality Assurance		x
Documentation		x
Development Planning		x
Project Risk Analysis		x
Verification & Validation Planning		x
Configuration Management	✓	
Selection of Methods	✓	
Code of Design Practice		x
Selection of Language	✓	
Selection of Tools	✓	
Use of Existing Software	✓	
Use of Diverse Software		x
<b>Software Engineering Processes</b>	✓	
Development Principles		x
Software Requirement Specification		x
Specification Process	✓	
Design Process		x
Coding Process	✓	
Testing and Integration	✓	
<b>Acceptance, Certification and In-Service Use</b>	✓	
Certification	✓	
Acceptance	✓	
Replication		x
User Instruction		x
In-Service	✓	

Table One: Def Stan 00-55 Considered Issues in Certification Compared with Current KBS Practices

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# Considerations For Implementing an Instrument Approach Decision Aid

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## 1. SUMMARY

This paper describes the prototype Approach Procedures Expert System (APES), developed at the Vehicle-Pilot Integration Branch of Wright Laboratory at Wright-Patterson Air Force Base. Specifically, the paper describes the types of advice provided by the APES, discusses the processes involved with its implementation, and presents a summary of the results obtained in a pilot-in-the loop evaluation of the APES. The APES is based on process flow models that capture the heuristics and procedures that define pilot processes in performing the various tasks of an instrument approach. The pilot-in-the loop evaluation results suggest that APES can improve pilot performance, increase situational awareness, and reduce workload, especially in a high workload environment. The evaluation also indicated some refinements to the APES algorithm and pilot-vehicle interface.

## 2. INTRODUCTION

The number of procedures, "rules of thumb" and extensive cognitive demands placed upon the pilot make the instrument approach well-suited for a decision aid application. The pilot not only must recall and apply specific instrument flight rules, remember correct task sequences, and calculate timings, but must also accomplish these tasks while simultaneously controlling the aircraft and continually monitoring its performance. In addition, the pilot may need to hurriedly replan according to air traffic control's (ATC's) redirection, requiring the pilot to reassess approach chart data, correlate that data with current aircraft position, and possibly adjust instrument command settings. When performed under adverse weather conditions with unfamiliar approaches, the potential for pilot error can dramatically increase.

The intent of the APES prototype is to reduce pilot workload and increase situational awareness by providing the appropriate advice to the pilot whenever it is most needed during a particular phase of the approach. The overall goal is to mitigate the number of accidents and incidents that are attributed to pilot error. An example of where APES may have benefited pilots is with the recent airline accident in Guam (Korean Air Flight 801). Preliminary reports indicate that the pilots apparently lost situational awareness when performing a non-precision approach, thought they were closer to the Guam airport than what they really were, and crashed into the terrain killing 225 passengers. It is hoped that

such accidents as the one in Guam can be averted if pilots are supported with a decision-aid such as APES to assist in the approach.

## 3. APES DESCRIPTION

The APES simultaneously monitors aircraft performance, informs the pilot of appropriate corrective actions when deviations occur, and provides procedural advice according to the phase of the approach (i.e., holding, initial approach, final approach, missed approach). In doing this, APES functions in two assistant roles: as an "advisory copilot" and as an "advisory pilot." As an "advisory copilot," the APES advises and prompts the pilot as a copilot would in a crew environment, such as advising when the aircraft deviated from assigned parameters (e.g., altitude, airspeed, etc.). As an "advisory pilot," the APES provides guidance relevant to the instrument flight rules (IFRs) needed for the specific phases of the approach. Audio is the primary pilot-vehicle interface for the APES. Visual messages are employed for redundancy and when the use of audio is impractical.

The basic architecture of the APES is shown in Figure 1.

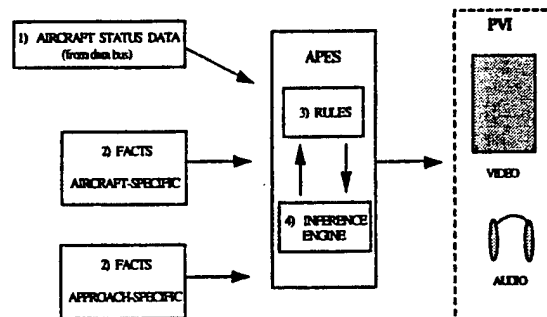


Figure 1. APES Architecture

As depicted, inputs to the APES are derived from three sources: a set of inputs describing current aircraft flight parameters, a database of aircraft-specific facts and a database of approach-specific facts. Most of the inputs to the APES are provided dynamically by the host system. Examples of the type of inputs that is used by APES include the following:

- Aircraft Status Data
  - Current Altitude / Heading / Airspeed
  - Current Navigation Aid Radial
- Aircraft-Specific Facts
  - Holding / Approach Airspeed
  - Fuel Weight

- Approach-Specific Facts  
Final Approach Course  
Minimum Descent Altitude / Decision Height

An aircraft-specific input file is created for each aircraft type in order to allow a generic APES to be embedded in aircraft (or aircraft simulators) of different types. An approach-specific input file is created for each approach type. This file is based on approach-specific process flow charts that identify approach plate parameters and generic pilot tasks and decisions that are required during a particular phase of an approach. An example of such a process flow chart is illustrated in Figure 2.

#### 4. APES DEVELOPMENT

##### 4.1 Knowledge Acquisition and Process Flow

The first step in the development of the APES is capturing the expertise of an experienced pilot through a knowledge acquisition process. This process involves conducting extensive iterative interviews with pilot subject matter experts to identify the precise steps required for flying the various phases of an instrument approach. The knowledge engineer then models the actions recommended by the expert pilot and creates process flow diagrams that represent the general sequence of tasks and decisions for flying instrument approaches.

The collection of process flow diagrams provide the foundation for algorithmic development to be implemented in the APES prototype. A representative example of the content of these process flow diagrams is shown in Figure 2. In this chart, the process flow for an approach-specific process is depicted. This process defines the sequence of pilot tasks and parameters specific to an approach. These parameters are currently depicted in paper approach plates.

##### 4.2 APES Implementation

The knowledge acquisition process is also used to develop a control scheme that enforces the proper sequencing of rules. The expert systems development tool used for APES is the C Language Integrated Production System (CLIPS) developed at the NASA Johnson Space Center (CLIPS, 1993). The CLIPS inference engine uses the Rete algorithm to activate a rule whenever one or more of its antecedents has changed. Each APES rule states the precise conditions (antecedents) that must be satisfied before that rule is executed.

The APES prototype is embedded in the Microprocessor Applications for Graphics and Interactive Communications (MAGIC) simulator at Wright Laboratory Vehicle-Pilot Integration Branch. The MAGIC simulation is driven by a generic F-16 aero model. The MAGIC cockpit control and display suite used for development of the APES prototype is depicted in Figure 3.

##### 4.2.1 Electronic Approach Plate Formats

The APES was implemented in conjunction with the Electronic Approach Plate (EAP). The approach plate

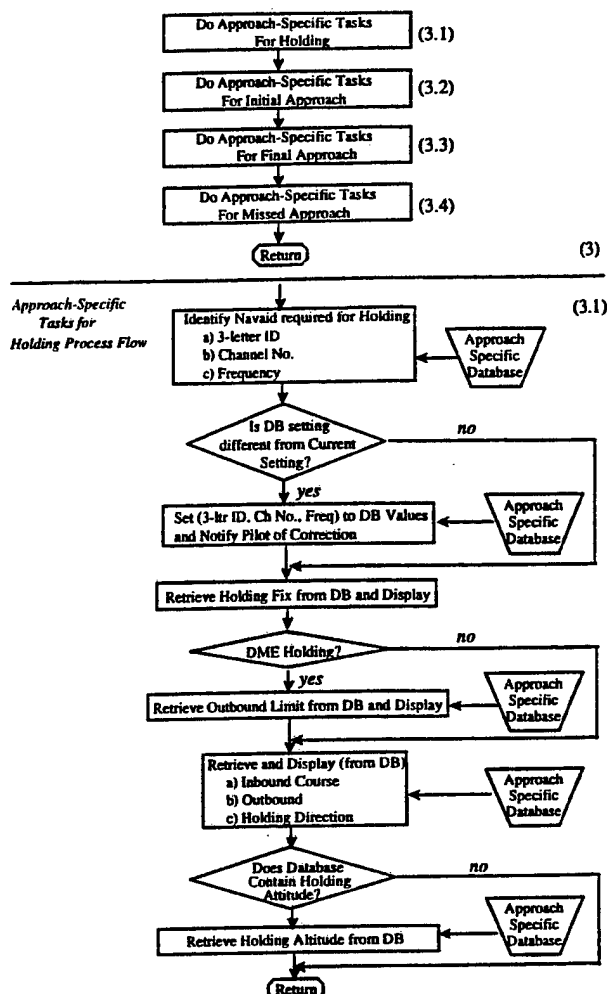


Figure 2. Approach-Specific Process Flow for the Holding Phase

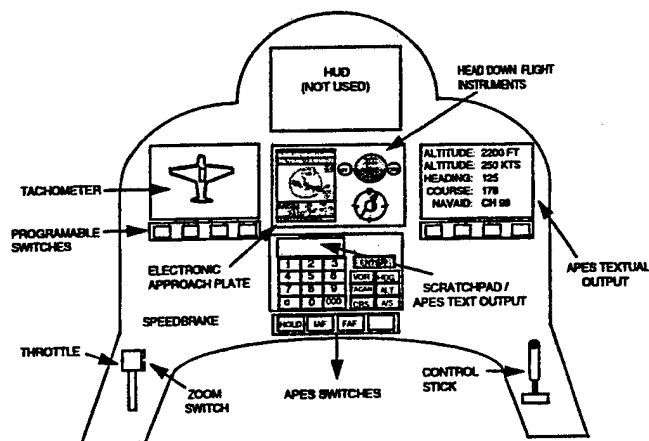


Figure 3. MAGIC/APES Cockpit

is a map that identifies all the relevant parameters (e.g., radio frequencies, course, altitudes) for flying the various phases of a specific approach. EAPS are electronic depictions of the paper approach charts. The EAPs are displayed to the left of the head-down flight display in the MAGIC cockpit (see Figure 3). Figure 4 shows



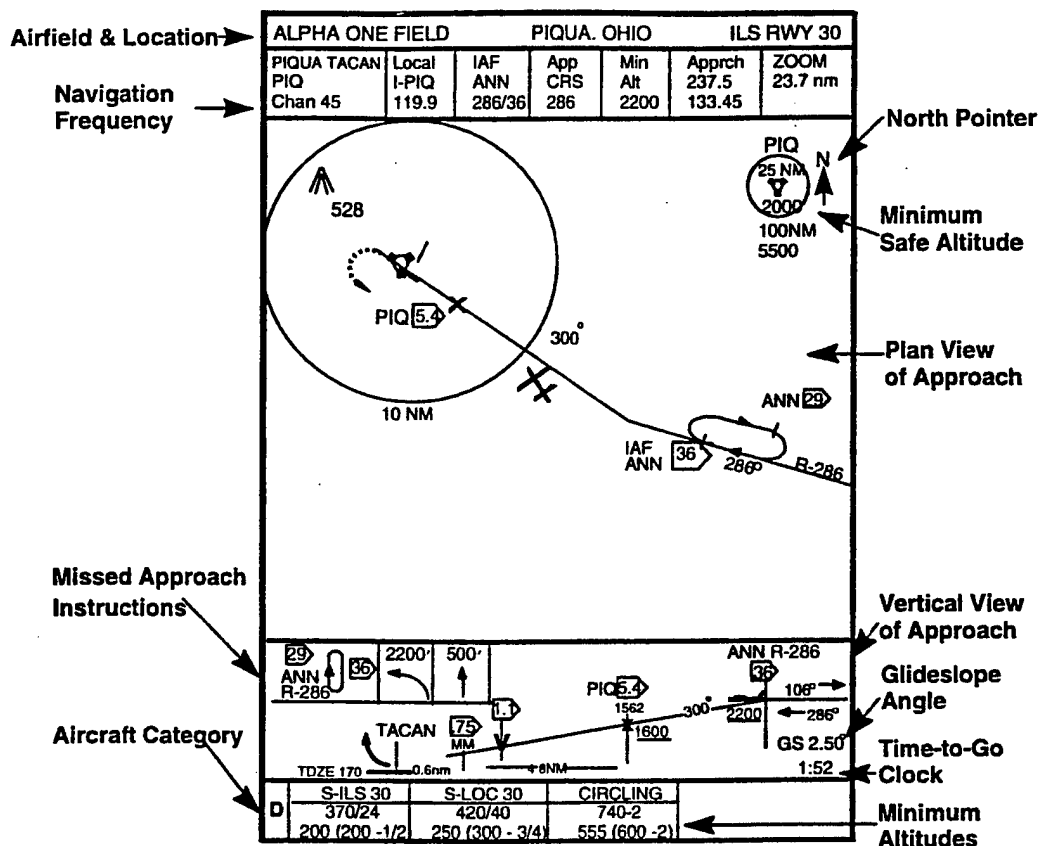


Figure 4. Representative Electronic Approach Plate Format

an example of the electronic approach plate format that was used in the pilot-in-the-loop evaluation of APES.

#### 4.2.2 APES Pilot-Vehicle Interface

The primary pilot interface for the APES is auditory. To output a voice message, the APES passes a text string to the voice module of the host system, which is responsible for generating the corresponding audio message. The voice module generates appropriate phrases by combining words listed in a vocabulary database of approximately 50 words.

APES voice messages are reinforced with textual output. The APES continually displays updated target values for radio channel/ frequency, altitude, airspeed, heading, and

course in a scratchpad area to allow appropriate command and course settings. APES also displays command settings for radio, altitude, airspeed, heading and course on a dedicated CRT.

Table 1 depicts the various types of deviation advice given to the pilot, which is part of the APES "advisory copilot" component. As shown, this advice is given for the following parameters: airspeed, altitude, heading and course. APES advises the pilot of a deviation and gives correction whenever the pilot deviates outside a parameter's tolerance window set by APES. For example, if the pilot deviates more than +/- 2 degrees from course, the APES "advisory copilot" component announces a new heading and turn direction to re-

AIRSPED	"Maintain XXX knots"	Desired airspeed displayed in the scratchpad for command marker setting
ALTITUDE	"Maintain altitude XXX"	Desired altitude displayed in the scratchpad for command marker setting
HEADING	"Come Right (Left) XXX degrees" "Turn (right/Left) Heading XXX"	Desired heading displayed in the scratchpad for setting of the heading "bug"
COURSE	"Turn (Right/Left) Heading XXX" "Maintain Course XXX"	Desired course displayed in the scratchpad for setting of the course on the HSI

Table 1. Deviation Prompts of the APES "Advisory Copilot" Component

PROCEDURAL PROMPTS		
DECISION AID PARAMETER	AUDITORY	VISUAL
TURN	"Turn (Direction) Heading (XXX)"	Textual display of direction appeared on the right CRT and in the scratchpad.
AIRSPPEED	"Set Airspeed XXX knots" "Maintain Airspeed XXX knots"	Displayed desired airspeed on the right CRT and in the scratchpad. Reversed video highlight Airspeed Select Button on lower CRT to cue for quick entry of command value.
ALTITUDE	"XXX feet (above/below)" "Minimum Altitude XXX feet" "Begin (Descent/Climb)"	Displayed desired altitude on right CRT and in scratchpad. Reversed video highlight Altitude Select Button on lower CRT to cue for quick entry of command value.
NAVAID	"Set Navaid Channel and / or Frequency (XXX / XXX.XX)"	Displayed desired freq./ch on right CRT and in scratchpad. Reversed video highlight Navaid Select Button on lower CRT to cue for quick entry of Navaid Channel and/or Frequency.
COURSE	"Set Inbound/Outbound Course (XXX)"	Displayed desired course on right CRT and in scratchpad. Reversed video highlight Course Select Button on lower CRT to cue HSI course entry.

Table 2. Procedural Prompts of the APES "Advisory Pilot" Component

intercept that course.

Table 2 shows the various types of procedural advice of the APES "advisory pilot" component. The content of procedural advice differs with the phase of the approach (i.e., holding, initial approach, final approach, missed approach). For example, when it is time to turn the aircraft onto the holding inbound course, the APES "advisory pilot" component gives verbal prompts and notifies the pilot of the appropriate heading and direction of turn to fly onto that course.

APES voice messages are reinforced with textual output which are displayed on the right CRT in the MAGIC simulator (see Figure 3). The APES continually displays updated target values for radio channel/frequency, altitude, airspeed, heading, and course in a scratchpad area, located on MAGIC's center CRT to allow appropriate command and course settings. APES also displays command settings for radio, altitude, airspeed, heading and course on a dedicated CRT.

## 5. PILOT-IN-THE-LOOP EVALUATION

Upon the completion of the APES prototype, a pilot-in-the-loop evaluation was conducted to assess:

- 1) the effectiveness of APES for supporting approach tasks and its potential for reducing pilot workload, increasing situational awareness, and improving performance.
- 2) the performance of the decision aid to determine if APES advice was accurate and timely enough to assist the pilot in flying instrument approaches.
- 3) the understandability and useability of the pilot-vehicle interface.

To accomplish these objectives, 16 pilots flew a series of instrument approaches in the MAGIC simulator. The

presence or absence of the decision aid, the orientation of the electronic approach plate (North-Up/Track-Up), and task difficulty (high/low) were varied across testing sessions. In the high task loading condition, pilots flew non-precision approaches, with wind gusts incorporated into the aeromodel, and were given no prior review of the approach. In the low task loading condition, pilots flew precision approaches, without wind gusts, and reviewed the approach plate prior to flying the approach. Flight performance, workload, situational awareness, and questionnaire data were collected and analyzed.

The results showed that the APES enhanced the pilot's ability to perform instrument approach tasks compared to flying the approaches without APES assistance. With APES assistance, pilots deviated significantly less from assigned altitudes during high task loading. See Figure 5.

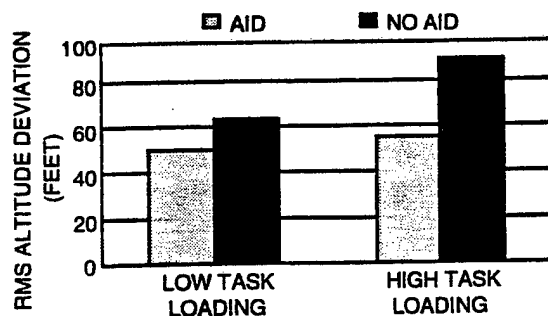


Figure 5. Task Loading as a Function of Altitude Deviation

They also deviated less from assigned airspeed during the initial and final approach phases. Using the Subjective Workload Dominance (SWORD) technique, pilots rated their workload lower with APES, especially

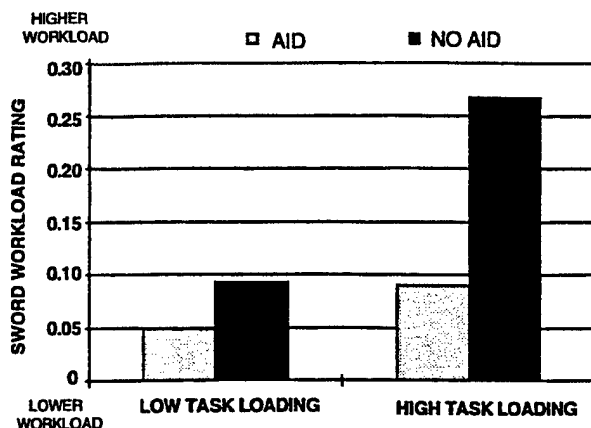


Figure 6. Decision Aiding and Task Difficulty as a Function of Subjective Workload

during high task loading conditions (see Figure 6), and their situational awareness higher with APES, independent of task loading. Study findings also indicate that APES effectiveness was not influenced by the orientation of the electronic approach plate (i.e., north-up or track-up).

Regarding the performance of the decision aid itself, pilots rated APES' accuracy, consistency and timeliness as above "moderately acceptable," however, pilot comments indicated that the deviation tolerance windows for APES voice activation may have been too stringent, especially the airspeed and altitude voice prompts. Also, the timeliness of the procedural prompts, given at the approach fixes, were reported as being slightly "hurried." Pilots rated the APES PVI (audio and visual) as "acceptable," although some refinements were indicated.

Regarding its overall utility, two-thirds of the pilots rated the overall utility of the decision aid for assisting in instrument approaches as "extremely beneficial." Pilots thought the decision aid enhanced performance on *all* of the approach tasks. Most pilots commented that the decision aid should improve flight safety; however, several pilots expressed concern with the consequences of being over-reliant on the system.

## 6. GENERAL ISSUES TO CONSIDER / IMPLICATIONS FOR FURTHER RESEARCH

As with any decision aid, careful consideration needs to be given to the known disadvantages associated with semi-automated systems. Because low-level decision making processes are automated, the pilot may view the system as a black box that generates outputs from inputs through some unknown mechanism, such as the algorithm. This may impair pilot confidence in the system and result in the pilot completely ignoring the advice of the decision aid. Conversely, too much trust and over-reliance on the decision aid may lead to reduced pilot situational awareness, which in turn, could adversely affect flight performance if the decision aiding system fails or an emergency occurs. Proper training of the decision aid logic is imperative to the success of a decision aid, enabling the pilot to develop an accurate mental model of the reasoning behind the advice. Equally important is proper design of the pilot-vehicle

interface that will allow the pilot to easily interpret the meaning of the decision aid advice.

The results of this study strongly encourage future development of the Approach Procedure Expert System (APES). Enhancement of the APES algorithm is one area for follow-on research. Future implementations of APES altitude and airspeed deviation advice may need to consider trend information. In its current implementation, APES could not provide explicit corrective altitude and airspeed advice (i.e., increase/decrease by XXX feet or XX knots) because altitude and airspeed were too dynamic for accurate input. APES procedural advice could also be augmented to provide a predictive rate of descent (i.e., VVI) to capture target altitude. In its current implementation, APES only periodically prompted the pilot of the target altitude.

Future pilot-in-the-loop studies should evaluate APES to assess its robustness across a diversity of approach types, including high-altitude approaches (only low-altitude were used in the current study) and non-typical approaches. Future APES implementations will also need to address potential conflicts between the APES audio advice and radio communications. This research should investigate pilot-selectable options for configuring the PVI (e.g., setting deviation tolerance windows for decision aid activation). Issues involved in implementing an intelligent agent for automatic adjustments of display and advice settings should also be examined. Finally, avenues should be investigated to determine the benefits of applying APES to other phases of flight, such as departures, airdrop and air-refueling operations and low-level routes.

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# Supporting Distributed and Ad-hoc Team Interaction

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## SUMMARY

Drawing on explanative models of team behaviour and cognition, this paper seeks to describe the challenges faced by ad-hoc and distributed military teams, which are increasingly common structures in modern warfare settings. These comments are made in the context of supporting evidence drawn from a recent survey, targeted at individuals with experience of operating in these teams. Issues addressed include the maintenance of essential teamwork behaviours, the development of shared situation awareness, and the special challenges faced by team commanders. Distributed and ad-hoc teams are examined with the added aspect of one, or more, members of the team potentially being electronic crewmembers (ECs). It is concluded that for these team settings, developers of future ECs should consider moving away from a functional model of 'task manager' for the EC, to one of team process 'facilitator'.

## INTRODUCTION

Distributed teams can be either a team with distributed skills, or more commonly one whose members are in some way physically dispersed, but who are operating towards the achievement of shared goals. Ad-hoc teams, consist of individuals brought together temporarily for the achievement of short-term goals, who are likely to have little, or no previous experience of working together. The use of ad-hoc teams in distributed structures is now typical of many modern Operations Other Than War (OOTW) and Joint Force operations.

In recent years, increasing research has been devoted to the application of Artificial Intelligence (AI) and Knowledge Based Systems (KBS) to aircraft cockpit environments. This has been reflected in the development of electronic crewmembers (ECs) to support pilot task conduct. In broad terms, much of the existing EC functionality is focused on monitoring system status, intelligently managing displays, dealing with system malfunctions, and offering situation assessment and mission planning advice. It is likely that further emphasis will be placed on dynamic function allocation (DFA) and increasing levels of system decision autonomy within future EC prototypes. In addition, thought has been given to expanding the EC concept to larger teams/crews (e.g. [1]). Inevitably, this also means assessing the opportunities for exploiting the EC concept in teams situated in the land systems and naval domains. With this in mind, and with the military's trend to use both distributed and ad-hoc

teams on a larger scale, it is important to ask questions about the impact and consequences of using EC's in these team structures, particularly those outside of the aircraft cockpit.

Research currently being conducted at DERA Fort Halstead (e.g. [2]) is seeking to better understand the unique challenges faced by ad-hoc and distributed military teams, and to develop support techniques to improve team effectiveness in these settings. Drawing on explanative models of team behaviour and cognition, the remainder of this paper will outline some of the difficulties faced by teams in these settings. Evidence is also presented from a recent survey, targeted at individuals with experience of operating in these team structures. In doing so, the implications for the insertion of one, or more, ECs into ad-hoc and distributed teams will be considered.

## TEAM INTERACTION CHALLENGES

The research at DERA Fort Halstead has examined ad-hoc and distributed team performance from a number of behavioural model perspectives. Morgans' et al (94) [3], theoretical model of team development provided a useful starting point for this work. They argue that there are two distinguishable tracks that develop within the team as it matures. There is the taskwork track, which centres on the operations-related activities undertaken by the team. The second track, teamwork, is represented in those behaviours

and activities that enhance the interrelationships, communication, co-operation and cohesion within the team. It is argued that through a series of development stages (i.e. forming, storming, norming), these two tracks gradually coalesce to facilitate effective and co-ordinated performance within the team. The importance of this model, is that this paper will argue that the traditional functional model for the EC may not be appropriate for effectively supporting those activities associated with the teamwork track, particularly in ad-hoc and distributed settings.

Building on the team evolution model, McIntyre and Salas (95) [4] identified a series of essential teamwork behaviours, which underpinned effective team performance. These were embodied in twenty principles. Key amongst these behaviours is performance monitoring, feedback, closed-loop communication and backing-up behaviours. Researchers at DERA Fort Halstead used these principles as a basis for a survey of the teamwork experiences of twenty-nine individuals operating in military ad-hoc and distributed settings. Based on this research, the following observations are made about these teamwork settings and the implications for EC development, beginning with the four essential teamwork behaviours described above:-

**Monitoring;-** In order to maximise team efficiency and to build up a psychological contract of trust among team members, the monitoring of fellow members' performance is considered critical [4].

Monitoring in distributed teams has to be largely conducted using various electronic links. Unfortunately this results in a loss of the richness of information passed between members, making accurate situation assessment of team and system states difficult [5]. In the survey conducted by DERA researchers, 86% of respondents argued that monitoring fellow team member performance was more difficult than in a co-located setting. A typical comment was that it was 'easier for people to hide their anxieties and problems'.

With ad-hoc teams, individuals may be reluctant to monitor, or may be unaware of the need to monitor, others performance. Ad-hoc teams have the additional problem that they typically have limited opportunities to train together and thus build up team norms associated with the establishment of team identity. Consequently, knowledge of fellow members' strengths and weaknesses is limited, and team interdependence is weakened.

**Monitoring – EC implications;-** Often interaction with the EC has to follow strict protocols, resulting in a reduction of available cues to monitor. In particular, the EC currently has little prospect of being able to interpret critical cues associated with anxiety, workload, fatigue, and risk-taking in team members. In addition, team settings are dynamic, with the team altering its task, function allocation and workload structure accordingly. This begs the question of what the EC should monitor, when, and how it could be made responsive to changing team circumstances. It has, however, been suggested that the EC could monitor task progress and completion, and make that information available to other team members. Alternatively, it could prompt the Commander, or other individuals, to actively monitor team members' progress.

**Feedback;-** As a result of monitoring team performance, information on team/task performance should be made available to other team members. This is a critical process for building up adequate levels of shared situation awareness within the team. More generally, feedback also facilitates team maturation, enabling individuals to develop an understanding of team norms for appropriate intervention.

As with the process of monitoring, it is proposed that an ad-hoc team with an immature sense of team identity and limited appreciation of team norms, will find it extremely difficult to provide and accept constructive feedback. This was confirmed by 62% of survey respondents. In addition, nearly 80% of respondents believed that the same was true of distributed environments, in comparison with co-located settings. Once again, it is postulated that the reason for this finding lies in the degraded quantity and quality of cues available across electronic media, from which the individual has to try and develop appropriate responses.

**Feedback – EC implications;-** It has been suggested that one of the biggest obstacles to human recognition of expert systems errors is the poor quality of feedback about the activities of the automated systems, such as EC's [6]. Therefore, if other members of the team are to effectively exploit the EC, it is imperative that the feedback provided by the system on its performance matches human team members' expectations. This could be in terms of content, time-scales for delivery of the feedback, and perhaps most importantly, appropriateness of feedback given. This might vary as a function of the experience of the other team members, and the range of operational situations encountered. The problem

of team turnover, resulting in ad-hoc team structures, is likely to add to what is a taxing challenge for EC developers.

However, if the EC was positioned less as an integral decision making member of a team, and more as an overseer of team process, it is possible to envisage how it could be used to prompt the initiation of feedback activities within the team. This could prove particularly useful in those ad-hoc team settings where interdependence is weak, and there may be reluctance to engage in these essential behaviours.

**Closed-loop communication;-** Although effective communication in any team setting is important, the process of 'closed-loop' communication is considered to be essential [4]. This is where an individual acknowledges receipt of information and the sender checks that the message has been interpreted correctly.

These communication protocols may be common to military settings, however it is important to note that shared communication does not automatically result in shared understanding [7]. In essence, without clarification or cross-checking, it is possible that messages may not be interpreted correctly by recipients. A typical comment drawn from the DERA survey was that, 'communications are the single biggest problem in all distributed operations'. Naturally, the number and nature of communication links in distributed settings is somewhat limited, with 65% of DERA survey respondents confirming that communicating over electronic media is not as effective as face-to-face interaction. The consequence is that fewer cues exist from which the sender of the information can draw accurate inferences concerning recipient interpretation of that data.

Unfamiliarity with fellow team members in ad-hoc teams also contributes to the difficulty of interpreting the meaning of restricted response information. In addition, it is also clear that the checking mechanisms required in effective closed-loop communication are less likely to be conducted in ad-hoc teams. It is hypothesised that this may be a function of inconsistent mental models held by team members, leading to false assumptions concerning recipient understanding of data. This issue is discussed in more detail later.

**Closed-loop communications – EC implications;-** A study of collaborative work on intellectually demanding tasks [8], highlighted the criticality of informal (i.e. short, unplanned, unstructured) communications. Like other computer mediated

communication systems, current ECs largely utilise 'pre-planned, relatively structured interactions with pre-selected communication partners'. In short, the opportunity to exploit informal interaction to enhance understanding and interpretation of information with ECs is restricted. A significant challenge for the developers of future ECs is to incorporate mechanisms for checking or ensuring that recipients understand information correctly. For example, this could be reflected in appropriate message prompts that help confirm shared understanding of commander's intent and team goals/roles. This support should also seek to resonate evolving state changes in this information.

**Backing-up behaviours;-** The fourth essential teamwork principle, is embodied in the teams willingness and preparedness to back fellow members up during operations.

Nearly 80% of those questioned in the DERA survey believed that it was more difficult for members of ad-hoc teams to know how and when to support (i.e. provide assistance to) each other, compared with mature teams. These concerns can be summarised in the following survey comment; 'there are natural inhibitions between people who are unfamiliar with each other. This is exacerbated where the ad-hoc team is joint, combined, or coalition in nature...where the more subtle uses of language are unfamiliar to one party and may be lost to other team members'. Ad-hoc teams do not have well-developed norms, or levels of trust, that facilitate the practice of backing-up behaviours. Individuals do not know the strengths and weaknesses of their colleagues and, as was also observed, 'are naturally preoccupied with orienting themselves to the new task/team environment'. In a different way, these problems are also common to distributed team settings. Even if team members have a greater sense of interdependence, restricted modes of communication degrade important cues concerning stress, fatigue and workload. Thus, it is not reluctance, but a lack of pertinent information upon which to base judgements, that delays timely interventions.

**Backing-up behaviours – EC implications;-** If team members are to accept back-up from ECs, then they must have implicit trust in the information or assistance provided by the system. Hicks and Ross (1990) [9] addressed the issues of trust and acceptance in the cockpit, of human/electronic teamwork. They found that overall, pilots welcomed automation that would relieve them of tasks during periods of high critical workload, and managed

mundane and routine monitoring tasks. However, they also noted that there was a great deal of mistrust and scepticism concerning the integrity and reliability of the automated systems. Thus, if an automated system, such as an EC, is flawed in some way, causing an error, trust in that system is easily destroyed. In human teams, such breaches of trust can be repaired, on the basis of confidence in humans learning from mistakes made. The recovery of confidence in the EC (without the explicit exposure of a similar learning process) is arguably far less easy to achieve.

As with the other teamwork behaviours discussed, a potential EC will always encounter difficulties in knowing when to intervene and engage in backing-up behaviour. The current paucity of automated systems in the land systems domain means that there is an absence of input information upon which a potential EC could operate decision rules governing such interventions. Should such infrastructures be developed, then an EC overseeing the teamwork, could monitor the progress of tasks against stated deadlines, and suggest to the team leader when potential problems are arising. For example, this could take the form of advice concerning the redistribution of workload, and might be particularly useful in those team structures where the team leader does not have direct sight of their team. It could also prove to be useful in ad-hoc teams whose members do not have the operational experience to know when or how to engage in backing-up behaviours. In the short term, a simple prompt function reminding team leaders to check team member status, could potentially promote timely backing-up behaviours within the team. Similarly, distributed team members could also be prompted for feedback on current and anticipated workload levels.

**Team leadership;-** Seven of the other team principles identified by McIntyre and Salas [4] focus on the critical role of the team leader in ensuring co-ordinated team and task performance. These include the need for the leader to foster respect with the team, to act as a role model, and to provide and receive feedback within the team.

As one respondent to the DERA survey noted, 'the greatest challenge to any leader is creating a team from a group of individuals'. Leaders of teams must provide a model of teamwork, which promotes leader perceptions of goals, roles and responsibilities, and expectancies concerning future team responses. This model can be difficult to communicate to ad-hoc team members who may bring different perceptions of teamwork, situational understanding, goals and in

multi-national teams, even conflicting political agendas. In ad-hoc and distributed settings, it is more difficult for team leaders to exercise their personal style and to foster respect among remote, or relatively unknown, team members' [2]. It is also more difficult to monitor performance and to offer feedback in distributed settings. Although the team leader has sight of team products, they may not necessarily see the process by which these products were arrived at.

**Team leadership - EC implications;-** The opportunity for an EC to adopt a highly autonomous team leadership, or task control role within the team settings described is arguably limited. Commanders of teams have to make decisions in an information environment characterised by high levels of uncertainty and ambiguity. Situation assessment and decision making will be conducted through a varying range of autocratic or consensual team processes. Developing an EC that reflects this adaptability in team leadership strategies would be a challenging prospect. Instead, it is proposed that an EC could assist a team leader to promote an effective teamwork model in ad-hoc and distributed teams. It could potentially assist in the rapid promulgation and confirmation of team goals, and could prompt, or assist the team leader, to monitor and offer feedback within the team.

Moving away from the largely behavioural perspective adopted by McIntyre and Salas [4] in examining effective team performance, the remainder of the paper will examine team functioning in these settings in terms of team cognition.

**Shared Mental Models;-** It has been argued that team members' exercise shared knowledge bases that enable them to accurately explain their task environment, and to anticipate the requirements and actions of other team members [10]. These shared mental models enable a team to adapt successfully to stressful situations, maintain shared situation awareness, and help trigger critical team behaviours, such as monitoring and feedback.

Compared with mature teams, 73% of DERA survey respondents believed that it was more difficult for ad-hoc teams to maintain shared situation awareness. In addition, 72% of respondents also asserted that ad-hoc teams were not as effective at anticipating the needs of their team members. Similar findings were recorded for distributed teams, in comparison with co-located group structures.

Ad-hoc teams lack the sense of identity and interdependence that facilitates the formation and



practice of shared mental models. Limited training time together as a team, frequently means that the development of adequate plans, contingencies and anticipated responses to possible situations may not occur, or may not be consistently shared across the team. In addition, team norms that facilitate the effective use of essential teamwork behaviours have often yet to be fully developed. The leader of these teams then faces the daunting task of trying to quickly establish these shared views, before the team must swing into action. This can be particularly challenging in those settings where the team must operate in a distributed structure.

**Shared Mental Models – EC implications;-** The processing of automated systems, such as an EC, is not easily open to direct review (or learning), making it difficult for team members to generate a mental model of the system [7]. In this sense, the EC is fundamentally flawed when viewed as a typical team member in these settings. However, it is suggested that an EC could potentially prove invaluable in promoting the early development of shared mental models and in assisting the maintenance of shared situation awareness in changing circumstances.

Research at DERA Fort Halstead has recently been initiated to establish how technology can be exploited to facilitate the exchange of information on goals, task progress, situational understanding and resource management within a team. This research aims to help team leaders to highlight gaps in knowledge, resolve conflicting team member views of critical information and to build and maintain shared mental models. In the future, a sophisticated EC could therefore help build up consistent mental models in an ad-hoc team, and maintain shared situation awareness in a distributed team. The dynamic prompting of essential teamwork behaviours could also enhance this process. An EC might also help build a better understanding of team member strengths, by making available skill profiles in a central database, and by providing an effective means for the distribution of information on team errors, and the recovery of those errors.

## CONCLUSIONS

In summary, it can be argued that the role of decision-maker, or task manager, for the EC in larger teams, particularly those outside of the aircraft cockpit, may not be appropriate. There are far fewer electronic systems integral to the planning, situation assessment and decision making process in land operating domains. Thus, there are currently fewer

interfacing electronic databases that can be exploited by traditional ECs. More importantly, ad-hoc and distributed team settings are dynamic, with the team altering its task, function allocation and workload structure accordingly. In addition, decision making and situation assessment products can be arrived at through a varying range of autocratic or consensual processes, depending on a range of impacting contextual factors. Developing a traditional EC, which is this adaptable to changing team decision strategies, would be difficult. The ad-hoc team also lacks the stability and predictability associated with those teams who exploit well-practised norms as part of the mature team process. Consequently, this makes it problematic to predict in advance how and when a potential EC should support team taskwork activities.

In light of these observations, it is proposed that the potential role of an EC in these team settings should be as a 'facilitator' of effective team process. The EC would therefore not have a direct controlling role in the taskwork activities of the team. Instead, the EC would help promote effective teamwork, by prompting the conduct of essential teamwork behaviours, such as monitoring and feedback within the team. The EC could also help the team leader to foster an early sense of interdependency and identity within the team, by promoting distribution of leader perceptions of team goals, member roles and interdependencies, at both a taskwork and teamwork level. It could also help to reflect dynamic changes of command intent and priorities to all team members, ensuring continued shared situation understanding.

It is also argued that the EC could have a key role to play in aiding the development of consistent shared mental models within the team. The future EC could effectively improve metacognition within the team, prompting the team to stand back from the decision making and situation assessment process, and ensuring that knowledge gaps are addressed, that assumptions are consistent, and that mental model conflicts are swiftly resolved.

To achieve the goal of an effective EC team process facilitator, an improved understanding of the cognition and behaviour underpinning effective team performance needs to be developed. It is also recognised that there are many technological challenges associated with meeting the requirements of the electronic team facilitator. However, if designers of future ECs are to effectively support team process in larger teams, particularly those that

are ad-hoc or distributed in structure, then these challenges must be met.

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## Cognitive Map Displays

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This paper will report DERA CHS work on cognitive requirements for future aircraft digital map displays for mission situation assessment, planning and re-planning tasks. In particular, the paper will consider the human factors issues of applying HEC teamwork concepts to the use of vector data map displays, supported by "intelligent" decision aiding technologies. It will present the idea of a Cognitive Map Display, where the map display system "knows about" how the pilot perceives, thinks and acts. It will demonstrate the implications through prototyping of a cognitive map display task.

Despite increasing use of aircraft Head-Up Displays (HUDs) and Helmet Mounted Displays (HMDs), map displays continue to remain the most complex displays of information in the aircraft cockpit. Dynamic mission information (position, route, mission and tactical information) is superimposed on complex geographical information. The term Digital Map Situation Displays (DMSDs) has been coined to emphasise the important interaction between geographical and mission information that occurs at the display surface. Because of the spatial nature of the information, and of the nature of the pilot's spatial reasoning map tasks, positional information and spatial relationships must be preserved. Unlike systems and flight information

in HUDs and HMDs, the ability to organise (i.e. separate, integrate, fuse, chunk) map situation information is limited. Spatial position is not a DMSD cognitive compatibility variable. Consequently, information superimposition and spacing problems often produce a DMSD image which appears cluttered, which is difficult to search and to interrogate, and often impossible to interpret reliably at a glance. Extensive design effort is needed on DMSD information coding, symbology, and colour to even approach an acceptable, organised image. Whilst the mission symbology can be refined, the content and format of geographical information remains largely unchanged from hard copy, paper maps. Differences may occur in the information presented in using different map scales for the required look ahead. However, the introduction of vector map data bases will provide the capability to address and select individual map features.

DMSDs provide information for the support for the critical pilot functions and decision making in mission planning, mission management and control. Support for in-flight situation assessment and mission re-planning is becoming an increasingly important issue. EC can provide pilot assistance in the following decision making tasks: assessing the impact of changes in the tactical and threat situation on the mission plan, in plan repair and in creating a new plan, and in critiquing re-planning with reference to the changing mission situation and objectives. Developments in digital map display vector data bases will soon provide new flexibility in information display for presentation, organised and tailored to the immediate situation. With EC assistance, this flexibility will enable the support to be more closely matched to the immediate decision making needs of both the situation and the user- i.e. mission and pilot context sensitivity- and to function more like a Cognitive Map Display.

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## **EC Support for F1 MotorSport**

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The Formula One industry is increasingly aware that they must rely on race tactics and strategy to provide consistent performances. Individual championships are important, but the Constructors Championship carries the main sponsorship drive. Therefore, it is in the team's best interest to coax the most consistent and error free performance out of their drivers, and provide a strategy that mirrors the driver's strengths and weaknesses.

The Electronic Crewmember's ability to offer the most direct method of achieving a goal, would enable the team to have an optimal strategy from which to base their driver's performance, when presented with a particular set of conditions. Examples would include:

- . Pit Stop Performance such as: in-lap speed, pit box braking point and angle of entry.**
- . Overtaking strategy, taking into account, position and length of race, track conditions, weather, car ability and driver ability.**
- . Risk Taking. Strategy should alter according to the individual riskiness of a driver. It is not feasible to ask a driver to alter his fundamental personality to fit a team tactic or car set-up. This aspect appears to pose a real problem in some teams.**
- . Number of pitstops can be correctly calculated to take into account the drivers ability as outlined above. In addition, factors may be calculated to take into account the way in which the driver performs with a full fuel tank and how hard he wears the tyres etc.**
- . Recording of behaviour during events resulting in loss of control, evaluation of the skills that were eroded. The system could also effectively demonstrate the disparity of a driver's actual performance in terms of skill-based responses in comparison to an ideal set of responses.**

Mapping and predicting an individual's behaviour, would enable the team in the pits to alter car set up and tactics as the events of a race unfold. In addition, it would provide a very useful tool in training and practice for improving skills and knowledge based decision making, by offering hard evidence of sub-optimal performances.

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# Combining Crew Assistant Functions of Information Management, Data Link, Mission Planning and automated Situation Assessment to improve Situation Awareness

by

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## 1 SUMMARY

The crews of today's fighter aircraft are confronted with workloads that often exceed tolerable limits. The demand for precision attacks in the presence of multiple constraints and the necessity to avoid collateral damage further complicate the tasks of the aircrews. This paper describes the development of crew assistant functions, which will reduce the crew workload and improve situation awareness of aircrews in combat situations. The core of these functions assist in situation assessment and situation display to the crew on air attack combat aircraft. These functions are supported by an airborne information management system, by data link internetting and inflight mission planning or replanning functions, that have to be integrated and used to derive the actual situation with regard to threats, targets and onside assets contributing to mission success. Further the required man-machine interface for presentation of the processed information to the crew in real time are described. These functions will first be tested and implemented on a ground based simulator. Later a flight test in a combat aircraft is envisioned.

## 2 INTRODUCTION

### 2.1 Human factors and situation

Even in a two seat air-to-ground fighter aircraft the workload of the aircrews often exceeds the limits, where crews can deliver optimum performance. Flexibility to react to changing situations is reduced. This applies especially during the actual combat phase of the mission. In today's combat aircraft informations are collected by a number of separate sensors like Radar Warning, FLIR and Radar and presented on separate displays. It must be checked against the preplanned mission data, leaving the task of processing and fusing all these informations and combining it with the mission plan and data into a valid situation assessment to the aircrew. This creates a considerable workload for the crew, which adds on top of the workload for flying the aircraft and operating the weapon system. Limitations in display representation further complicate this task.

Consequently a main issue in present programs for onboard crew assistance systems is the enhancement of the situational awareness of the crew by implementing automatic functions for information and data fusion, automatic situation assessment and situation display to the crews.

### 2.2 Integration of external information sources to improve situation awareness

Another shortcoming reducing situation awareness of the crew is an information gap after a mission has been launched. If only high frequency voice radio is available to forward last minute information on target and threat states to the airplane, little information can be delivered and the aircrews have only very limited onboard capabilities to perform adjustments in the mission plan and execution, if the tactical situation has changed. Usually target and threat information is several hours to days old and a significant situation change results in a mission abort.

If the mission is part of a combined air operation, formation keeping and coordination with support and escort aircraft within the flight must be pre-planned and performed rather rigidly, leaving little room for flexible reaction to changing situations.

These shortcomings can be reduced significantly by introducing a data link internetting of mission aircraft, command authorities and intelligence sources, which can be maintained throughout the mission.

### 2.3 Integration of onboard mission planning and execution assistant functions to maintain situation awareness in changing environments

In order to maintain situation awareness in a changing environment and to make best use of data link and other information and the onboard real time situation assessment function, inflight mission planning and replanning functions and mission execution assistant functions are added to the system.

The mission planning functions allow an inflight replanning of a mission, if threat or target situation changes and rebuild a situation assessment under

the new conditions to maintain situation awareness of the aircrew. The mission planning function relies on a target, threat and terrain data base to build a situation representation within the mission computer of the aircraft. Terrain masking and threat capabilities like detection ranges, firing ranges, susceptibility to ownship ECM and self defence measures must be modelled into the situation assessment as well as target vulnerability and possible ownship attack maneuvers to create optimum attack routes and profiles under changing conditions and to assess the resulting new situation correctly and display it to the aircrew. The new mission parameters must be transferred to the aircraft navigation and auto attack systems after approval by the crew and the execution must be assisted to keep the crew workload at acceptable levels.

### 3 DESCRIPTION OF THE INFORMATION MANAGEMENT AND CREW ASSISTANT SYSTEM FOR SITUATION ASSESSMENT AND DISPLAY

#### 3.1 Structure of the information management and crew assistant system

The information management and crew assistant system consists of the following modules (Fig. 1). The crew interface handles the display outputs to the crew and accepts crew commands. The main situation display is one of the weapon system officer's color head down displays. Due to the complex information to be presented a color coded display must be used. The main interface is with the WSO. The information management distributes data from and to the crew interface to the functional modules. These are:

- situation assessment and display
- threat assessment
- mission planning and execution
- data link processing
- data bases / data base management

The data link module is connected to an onboard MIDS-terminal, which can be connected to external MIDS or JTIDS ground or airborne terminals within a JTIDS net.

#### 3.2 Functional modules of the information management and crew assistant system

##### 3.2.1 Situation assessment module

The situation assessment module performs eight main tasks:

- determine all known threats along the attack route
- compute threat ranges, terrain masking and resulting threat areas
- compute threat cost functions

- determine threat total cost along pre-planned flight path and assess situation
- compute situation display formats
- monitor threats and invoke threat evasion, if threat gets in firing range
- monitor fuel reserves and own assets and invoke replanning, if reserves are low
- monitor timing and time over target and adjust command speed
- update threat and target data base from ownship sensor and data link data

If a route planning based on the situation assessment results in too high risk or too high fuel consumption or too late time over target, the route will be recomputed with ECM applied, which usually should result in a shorter route and / or reduced threat risk.

If this still is not sufficient, at pilot's request the allowable risk factor can be elevated and a more direct route with higher risk can be selected or the mission can be aborted.

The route planner also can be forced to circumnavigate "no fly" areas and fly through predetermined corridors for ingress and egress from the target area.

##### 3.2.2 Threat evasion module

The threat evasion module is (Fig. 3) invoked by the situation assessment module, if a known threat comes into firing range. Main tasks of the threat evasion module are:

- compute radar burnthrough range against ownship, request ECM, if applicable and sufficient to neutralise the threat
- run onboard SAM simulation, computing possible missile shots at the ownship to determine the potentially most threatening shots from any SAM station in range and alert the crew and propose the best available defensive action
- determine timing and flight path of optimum evasive maneuver with or without ECM support (chaff or towed decoy)
- determine timing and flight director indicator for evasive maneuver, adjust commanded speed
- compute situation display format for self defence situation

##### 3.2.3 Route- and attackplanner module of mission planning

The route- and attackplanner module (Fig. 4) is invoked by the situation assessment module after a



deviation from the preplanned course or after changes in the threat or target situation or if own assets run low and prohibit execution of the preplanned mission or by crew request. Main tasks of the route and attackplanner module are:

- compute threat optimized route from ingress point to the attack corridor and back to the egress point
- support radar navigation updates
- support precision target aimpoint location
- compute flyable route from optimized route with low level profile
- perform formation planning for multi-ship formation (up to four), deconfliction in target area and coordination with mission control via data link
- compute waypoints, command altitude and speed and attack computer settings
- compute fuel consumption
- compute timing and time over target
- compute planning display format

Main purpose of these functions is to permit inflight retargeting and replanning of a running mission and to react in real time on external situation changes.

Another application is for missions against mobile targets, which can be set up completely only after the flight is in the air and using a reconnaissance-attack interface via data link to direct the attack force to the target in real time.

### 3.2.4 Situation display module

The situation display module collects information from the situation assessment, threat evasion and mission planning modules, decides which information is most urgent for the crew now and composes the relevant information content into one of three main situation display formats (Fig. 5):

- situation display
- threat evasion display
- pre- / replanning display

### 3.2.5 Data link processing module

The data link processing module (Fig. 6) is running all the time as a background process and channels in- and outgoing information through the data link.

Main tasks are:

- unpacking, decoding and selection of incoming data
- data fusion of onboard data base, onboard sensor and incoming data link data
- extraction of relevant command, formation and mission planning update information from incoming data stream

- message composition for outgoing information
- operation of data link transmit and receive modules within a selected JTIDS-network

## **4 EVALUATION OF SYSTEM**

The information management and crew assistant system will be installed on a two seat Tornado flight simulator and can be tested in a simulated air-to-ground mission scenario with simulated opposing and allied forces. There the merits of the system can be evaluated in a simulated combat environment and necessary improvements to the system can be identified.

In a second campaign this evaluated system will be installed in a Tornado test aircraft in a pod based system to keep the necessary aircraft modifications as small as possible. This system will be flight tested with an AWACS-JTIDS ground station as data link partner station and evaluated.

## **5 CONCLUSIONS**

The presented research and development activities will provide an advanced cockpit avionics system capable of improving the aircrew's situational awareness in a combat situation, reducing the crew workload during critical situations and improving the flexibility of aircrew and aircraft. Furthermore the interoperability with allied air forces will be improved by providing better command and information flow via the data link connection, which will be especially important for multinational missions within Rapid Reaction Forces.

## Structure of Crew Assistant System

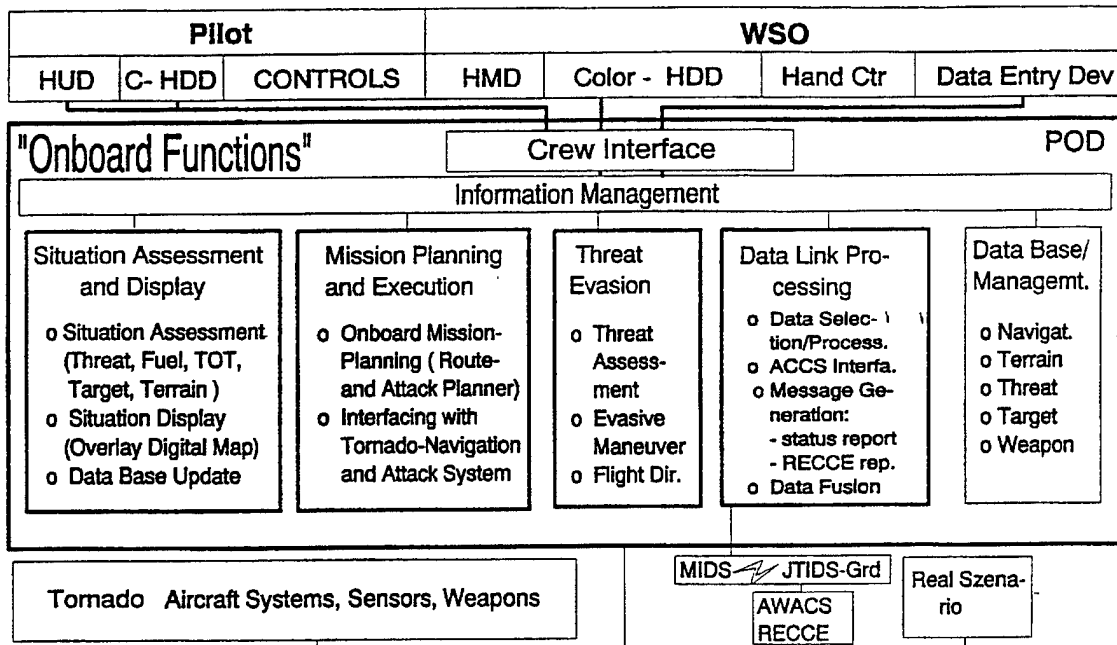


Fig. 1

## Situation Awareness Module for Crew Assistant

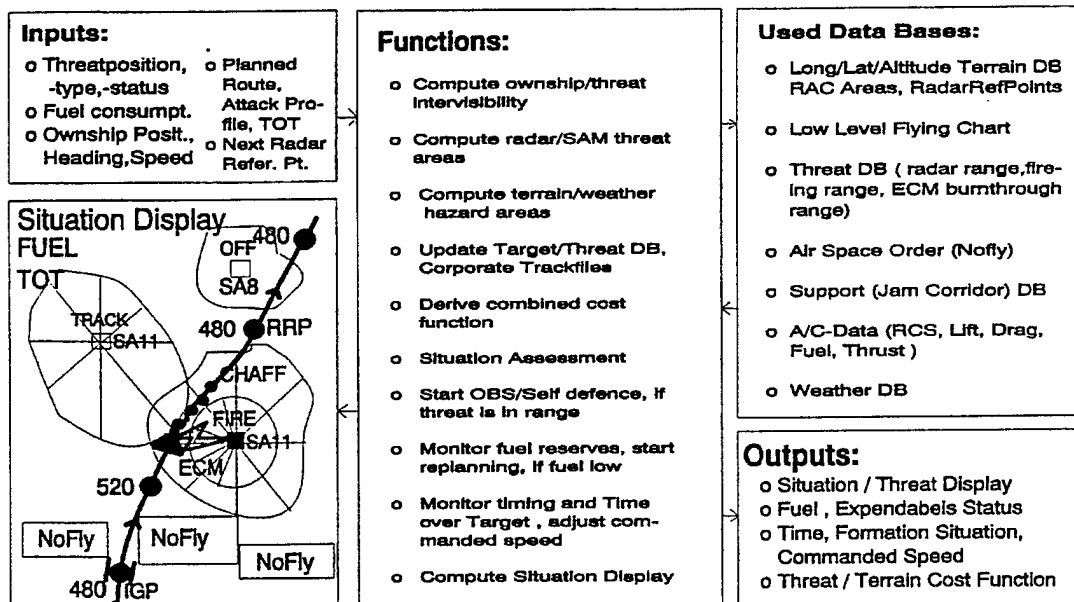


Fig. 2

### Threat Evasion Maneuver Module for Crew Assistant

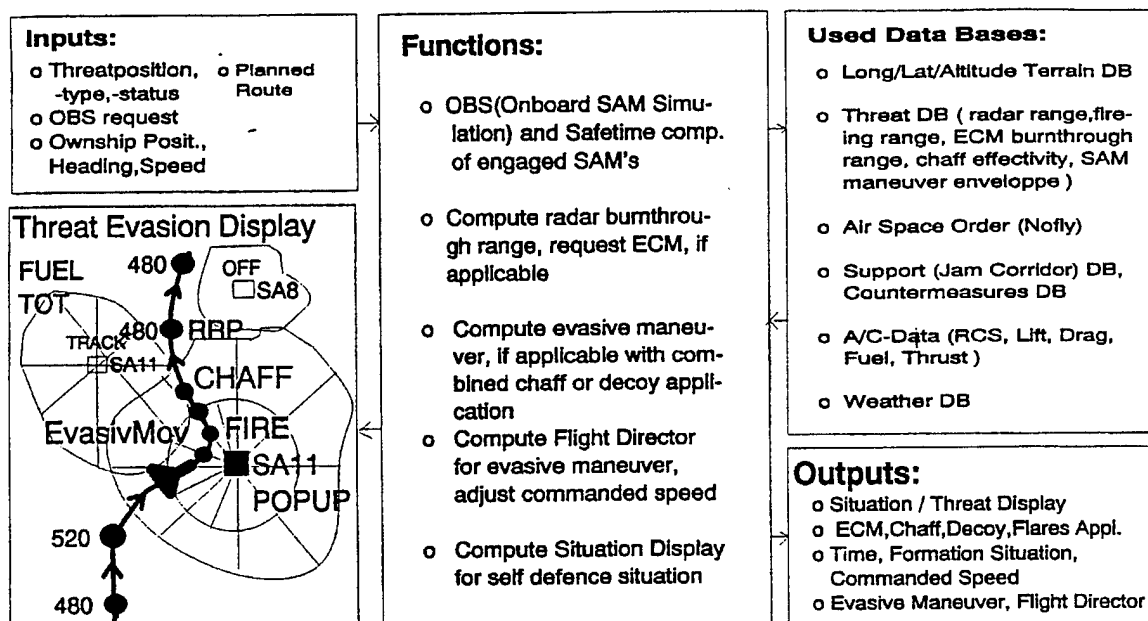


Fig. 3

### Route- and Attackplanner module for Crew Assistant Ground Attack

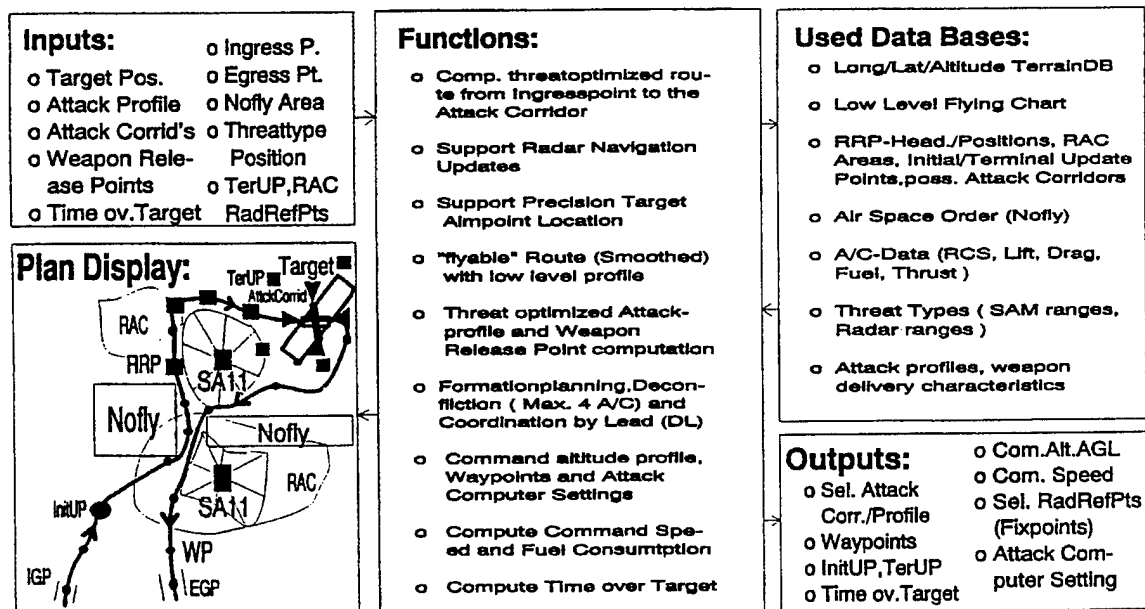


Fig. 4

Situation Display presented on 3 display formats:

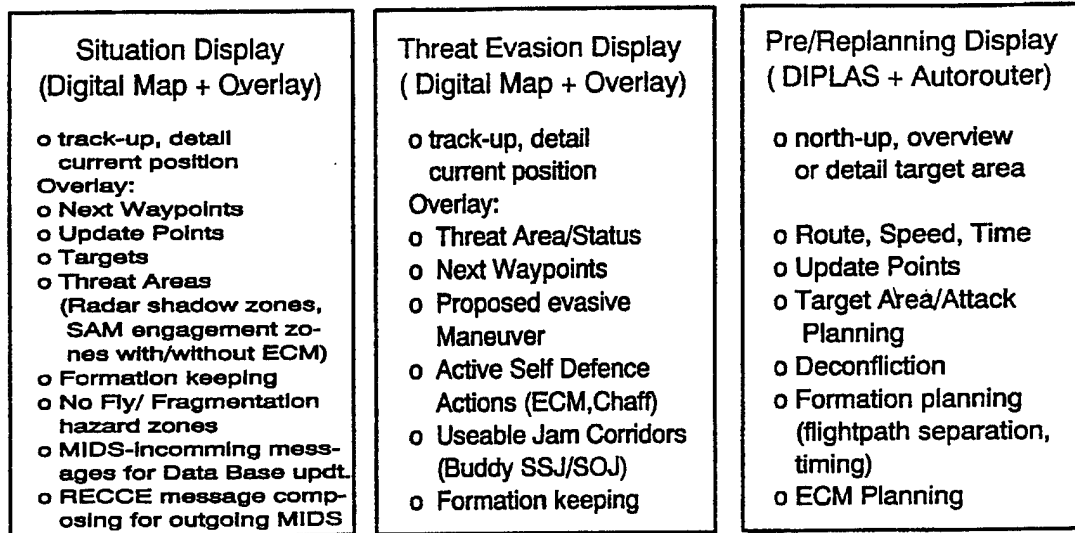


Fig. 5

### Data Link Processing Module for Crew Assistant

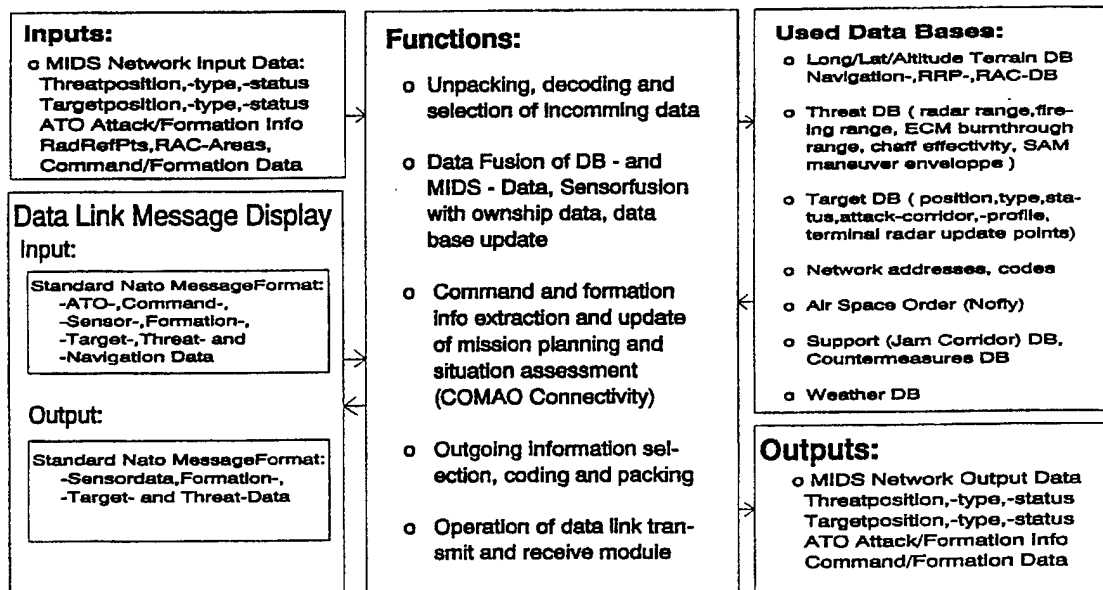


Fig. 6

## **Human-Electronic Crew-Test and Evaluation Issues**

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This paper will discuss the issues arising for aircraft test and evaluation (T&E) from the concepts of the Human Electronic Crew. The role of T&E in aircraft acceptance and the problems of man-in-the-loop assessment will be outlined. Current T&E methods for evaluating aircrew systems will be described, in particular the approaches used for assessing crew workload and performance. HEC T&E issues associated with human-computer interaction have beginnings in the introduction of digital avionics and automation of mission systems, and associated new cockpit technologies, from the late 1960s and early 1970s. These technologies have dramatically changed the nature of aircrew tasks. Beginning with the Harrier GR1 and Tornado Mk1 programmes, through upgrades such as to Jaguar, to the current programmes such as Merlin, attack Helicopter, and Eurofighter, aircrew tasks have become more about thinking than doing, and more cognitive than physical in nature. The need to assess aircrew mental workload, teamworking performance, and the useability of cockpit systems, in a scientifically valid, quantifiable and reliable manner, has become an increasingly important issue for aircraft T&E. DERA DTEO have had recent experience with glass cockpit automation T&E issues, through the C130J programme, and arising out of the ESR Future Large Aircraft project. The T&E issues and human factors lessons learnt associated with the use of advanced cockpit automation technology, arising from these programmes will be the basis of this paper.

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# Automated support for Command and Control (C<sup>2</sup>):

## *Experience from a naval technology demonstrator*

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*Any views expressed are those of the authors and do not necessarily represent those of the Department/HM Government.*

### Abstract

Modern warships are increasingly likely to be engaged in littoral warfare and combined operations with other ships, aircraft and land forces, employing sophisticated weapons and techniques intended to maximise effectiveness and minimise own-force casualties, expenditure of munitions and collateral damage. Access to information is vital for the detailed situation awareness and precision demanded by such complex scenarios.

The command must also be able to react rapidly when faced with fast-moving stealthy threats employing sophisticated deception and high-speed, high-accuracy weapons. In addition to sea-borne threats, a wide range of land-based weapons may be deployed against warships close in shore.

The consequent development of high-bandwidth communications for the exchange of intelligence and force sensor information, and increasingly sophisticated on-board sensors, have resulted in an increase in the information available for Command and Control.

High data rates demand rapid processing if the command is not to be overwhelmed by data. Because of this, high levels of automated support are already implicit in the requirements for future UK Royal Navy combat management systems.

Technology demonstration is a key tool with which to research the provision of sophisticated and effective automated support for command decision making. As well as providing real-time animation of the algorithms and techniques of automation, often in an operational context, technology demonstrators also address critical technical issues involved in procuring and

integrating components, both hardware and software, of future systems.

The UK Defence Evaluation and Research Agency (DERA) has developed the Data Fusion Technology Demonstrator System (DFTDS) for combat management systems research. The DFTDS is a large-scale prototype knowledge-based system for real-time data fusion. It provides automated support for the naval Command and Control functions of tactical picture compilation, situation assessment and reactive resource allocation by encapsulating these functions in software modules employing rule-based artificial intelligence techniques. The DFTDS is enabling DERA to:

- identify combat management functions that can benefit from automation, distinguishing these from others which may be high risk, or where the benefits of automation are less clear;
- develop measures of performance for automated systems;
- successfully apply knowledge-based systems to provide real-time automated assistance;
- fuse live data at sea in an operational environment;
- investigate sensor and other data interfaces required to interact with automated combat systems;
- investigate the use of databases in data fusion;
- implement a flexible, reconfigurable MMI;
- study novel forms of data input such as voice input;
- study changes in the role and responsibilities of operators.

### Introduction

The principal enabling technology to be discussed is KBS (Knowledge-Based Systems) and its application to the automation of functions within an afloat Combat Management System (CMS).

This paper provides a brief description of the DFTDS, followed by a discussion of lessons learned in providing automated support for shipborne Command and Control, based on experience in the laboratory and at sea in the users' environment.

## Data fusion at sea

An important function of Command and Control at sea is the extraction of information from all available data in order to describe the real world tactical environment of the ship. In existing systems, this is first accomplished by manual compilation of the tactical picture, consisting of vehicles (ships, aircraft, missiles etc.) operating in a tactical context.

Vehicles in the tactical picture may be supported by a variety of evidence from different sources, i.e. the data is fused. The identity, position and intent of vehicles is then used to reason about the tactical situation and to determine an appropriate response. In modern maritime warfare, with anti-ship missiles capable of speeds up to 1000m/s, Command and Control functions have become increasingly time critical.

## DFTDS functionality

DFTDS takes in real-time data (e.g. position, course and speed) from own ship's sensors (e.g. radars, sonars, IFF, ESM); other real-time inputs are ship's position data and operator input entered manually via keyboard, tracker ball, and an experimental voice input system used to enter identity overrides. DFTDS also takes in near-real time data from other ships' and aircrafts' sensors via datalinks. Non-real time frequently changing data such as IFF codes, plans, intelligence, signals etc. are entered by the operator into the DFTDS' operational database. Fixed data such as shore line and air lane positions are available to the DFTDS via its geographic database. A KBS, implemented in the data fusion module, fuses this data and presents it to the operators in a tactical picture.

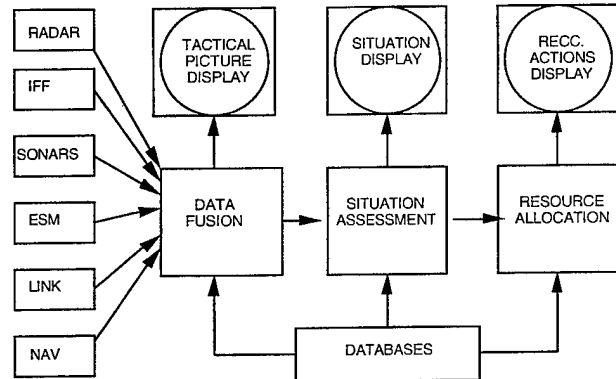


Figure 1: DFTDS block diagram

Further KBS modules use the fused tactical picture to assist the command in assessing the situation (the situation assessment module) and recommending actions to be taken (the resource allocation module). These modules are less mature than the data fusion module, hence this discussion will concentrate on data fusion for tactical picture compilation.

## Data fusion mechanisms

DFTDS is capable of fusing a variety of data types (reals, integers, enumerations, associations) from a numbers of sources (real-time, near real-time, non-real time changing; and fixed). An approach to data fusion that considers all possible combinations is untenable due the resultant combinatorial explosion of possibilities: modern sensors are capable of holding tracks on hundreds, sometimes thousands, of objects simultaneously; the capacity of tactical data links is continually improving; increasingly responsive database management systems are capable of providing large amounts of detailed data within very narrow time constraints.

DFTDS overcomes these problems by adopting a hierarchical approach to data fusion. In summary, this involves a two distinct stages, correlation and combination.

In the first stage, data from similar sensors is fused, e.g. an own-ship target indication radar track with an own-ship navigation radar track; similarly, data from the own-ship bow-mounted sonar is fused with data from the own-ship towed array sonar. In order to fuse, tracks must meet a number of track correlation criteria (e.g. environment, speed, position).



The result of this fusion of data from similar sensors is a representation intermediate between tracks and vehicles, referred to as a multi-track. Multi-tracks are of different types according to the source of their associated tracks. Multi-tracks of different types that satisfy the multi-track correlation criteria are then fused to create vehicles. Figure 2 below illustrates the process, where V is the vehicle, C is a confirmed correlation, MT is a multi-track, and T is a track:

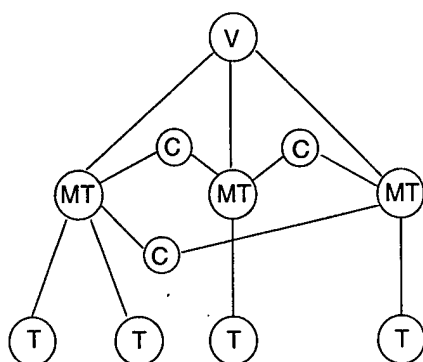


Figure 2: Data fusion hierarchy

Correlations are continually re-assessed as tracks are updated. Updates that fail to satisfy the correlation criteria, together with new tracks, start the correlation process over again. The result of the first stage of the fusion process is to populate the tactical picture with vehicles, either as point or bearing only.

The second stage of the fusion process combines track information with collateral information such as IFF, air lane status (e.g. in lane, crossing lane, out of lane - assessed by reference to the geographic database), behaviour assessment (e.g. fast closing contact), data link assessed allegiance, emitter identity, etc. The result is to ascribe an allegiance (friendly, neutral, hostile, unknown) and an identity to vehicles in the tactical picture. The allegiance assessment is tagged as possible, probable or confirmed by consideration of the weight of evidence and the war state, e.g. a vehicle considered 'probable neutral' in peace time may be considered 'possible hostile' in time of war.

The tactical picture is now available for display to the operator, and is also passed to the situation assessment module to identify groupings and threats. Threats are then

passed to the resource allocation module to recommend appropriate actions to the operator.

It should be noted that the correlation criteria and weights of evidence permit a degree of flexible parameterisation of the KBS reasoning process. Changes to parameters may be achieved at system start-up, or at run-time, allowing the operator to change the response of the KBS.

## Tactical picture display

DFTDS represents the first attempt in a UK RN Operations Room to use colour and a windows-type interface in an electronic tactical picture.

Display of multiple windows is possible, and windows may be moved and sized dynamically. This flexibility means that terminals may be configured during system run-time to suit particular warfare specialisms, e.g. air, sub-surface etc., reflecting RN doctrine for the organisation of Operations Room teams.

As much information as possible has been included in the non-standard symbology: shape is used to represent environment, e.g. an aircraft-shape symbol for fast air vehicles; orientation for assessed heading; colour for allegiance, e.g. red for hostile. Symbols filled with colour are held live, hollow symbols are those being dead-reckoned. Land and sea are represented in plan form, coloured green and blue respectively.

Data used in the fusion process such as airlines, sector screen plans, navigation features etc. is also directly available to the operator in the tactical picture as graphical overlays, further enhancing operator appreciation of the tactical situation.

Selecting an object in the tactical picture by means of the tracker ball or mouse brings up further windows containing a mix of graphics and text that provide information about the vehicle and its supporting tracks. Selection of fields in these windows, such as the assessed allegiance, brings up further windows that explain the system's reasoning.

The data fusion process is made visible further by providing the operator with graphical displays at the track, multi-track and vehicle levels. Various filters are available that allow the operator to display selected sources, environments and allegiances.

## Operator interaction

Although the operator may work with the vehicle-level tactical display alone, he can, by use of the track level window and by use of vehicle explanation windows and other windows such a plan displays, obtain quick access to the track level and other data supporting a DFTDS vehicle hypothesis.

Manual override facilities allow the operator to correlate and de-correlate, and to change the identity of contacts.

A concise history of the data fusion associated with a vehicle is also available to him. This visibility of the data fusion process is facilitated by KBS: it would not, for example, be possible to provide the same intuitive explanations if neural nets were employed.

## System size

The DFTDS consists of around 350,000 lines of Ada83 code, makes extensive use of commercial-off-the-shelf (COTS) hardware and software, and has approximately 900 rules, of varying complexity, in its three knowledge bases. It has taken about 200 man-years to construct.

The sea-going DFTDS, dating from 1991, was hosted on DEC Vax/VMS and Sybase RDBMS. Apart from basic shock-mounting of the rack cabinets, the system was not ruggedised in any way. Colour graphics were provided by five Sigmex colour graphics workstations. At sea, the DFTDS COTS equipment proved to be reliable and rugged. Recently, in the laboratory, the software has been re-hosted on DEC Alpha/OSF, and work is in place to move to an open UNIX system.

## Knowledge representation

KBS is a technology which, in principle, enables any available (expert?) knowledge for solving specific problems to be engineered in software. It is also a methodology which prescribes a prototyping approach to development, a programming style emphasising visibility of the encapsulated knowledge to non-computer specialists and a user interface providing explanations of the machine reasoning. One may regard KBS as a software engineering technology for complex human/machine software intensive systems; it is thus well suited to complex Command and Control functions in

which data is not simply stored or displayed but is combined, transformed and interpreted using scientific and expert knowledge of the application domain. It enables complex automated support functions to be implemented as shown by the DFTDS.

The main limitation of KBS is that it is restricted to fixed knowledge of a specific nature - it is not to be regarded as intelligent in the human sense. In particular, although the reasoning process may be adapted by changes to rule parameters, it has no learning capability. The adaptability that parameterisation provides enables the developer to fine-tune the KBS, however the role of such adaptability in the field has not been researched. If a Command System modified its rules from experience of many different situations and uncertainties, different ships would end up with different sets of rules. Furthermore some of these rules may have been modified as a result of inappropriate lessons being learnt from the many different situations and uncertainties.

Given that the knowledge is static then the problem that the KBS solves must also be static, or at least very slowly changing. It must be a problem that is well understood and which will persist for a considerable time - certainly much longer than it takes to develop the KBS. Development time-scales longer than a few years are unlikely to be useful in the Command and Control application domain and even when developed, the KBS will have to be continuously maintained in order to keep it up to date.

It might appear that a learning or self adapting capability would overcome the fixed knowledge limitation and this is being actively explored in the research community. Learning systems are not yet practical except in very restricted domains, and may not be appropriate for the Command and Control application, where visibility of the reasoning is crucial to user confidence.

It is tempting to look at Command and Control systems as performing a number of objective, describable, predetermined functions and believing that each can arbitrarily ascribed to human or machine. However it should be recognised that although a set of necessary functions can be described and indeed supported by KBS to a considerable degree (as proven by DFTDS), there is still a necessary and essentially subjective human element which must not be excluded.

## **Knowledge elicitation**

Builders of a KBS will meet subjectiveness early in the knowledge elicitation process. In DFTDS, one example occurred when attempting to formulate rules for assessing whether a vehicle is friendly, neutral, hostile etc. Five different people, each of whom had had recent command experience, were asked what assessment they would give in a tactical example. Perhaps not surprisingly, there were three different answers. This and other similar experience has lead us to deduce that it is impossible to put into a KBS reasoning which will reflect every human's thinking when judgement is called for (automation of reasoning processes cannot universally satisfy judgmental criteria).

## **Data representation**

The accuracy and reliability of data fusion is crucially dependent on the quality of information available from sensor and communications systems. In the past the process of extracting information and control of quality was entirely a human responsibility but now we are beginning to rely increasingly on automatic or semi-automatic information extraction. Unfortunately, though sophisticated, the technology for this automation still has many failings especially in controlling quality of output. In our experience this issue has been the biggest limiting factor in the performance of KBS functions. The quality of information can be highly inconsistent, and few if any of today's sensors provide adequate measures of the confidence which may be placed on data they report.

The performance of data fusion at sea can be degraded by poor position registration between ships and aircraft participating in the tactical datalink. This can lead to the appearance in the tactical picture, for example, of two air raids - one held by own-ship's radar, the other reported over the datalink - when in fact there is only one. Algorithms were developed in DFTDS to automatically correct for such position errors, but in some cases operator intervention was required to initially establish correct registration. Operator intuition or appreciation e.g. 'I know the link from HMS UNKNOWN is bad today and I make due allowance' were of great value in such situations.

Simulation of improved sensor inputs has shown that satisfactory data fusion performance is only likely to be reached with improved sensor processing. Therefore there is a practical limitation on any Command and Control system imposed by the practical limitations on their data sources. This limitation has been highlighted by the DFTDS trials programme. Although the DFTDS has demonstrated that KBS are capable of usefully reasoning with data of widely differing types, their inherent lack of flexibility means that they are prone to error if real world information is represented to them in a mis-leading way.

## **Data elicitation**

All military Command and Control systems require information from signalled messages: for example, the position where a fighter aircraft is to patrol is promulgated in a signal and this information can be used in the identity hypothesis.

Signal data must, however, be entered in a rigid format for a computer to be able to parse it and then make use of it. In practice, entering signalled messages like this by hand was known to be time consuming and error prone. The possibility of entering signalled messages automatically into DFTDS was considered but when relevant signals from an exercise were analysed, it was found that none was amenable to automatic interpretation. In each case the format laid down in the relevant NATO publication was not strictly adhered to, because humans can interpret and so do not need to follow rigid rules; indeed, if they did they would find it very restricting.

One answer to this is to enforce on senders of messages compliance to formats. However, if this were to be done, the sender would not be able to communicate everything that he felt he wanted to; for example, he might want to amplify his thinking behind ordering a ship to a specific position, or indeed may wish to promulgate policies for positioning rather than specific positions.

Therefore from our practical experience we deduce that there is a limit to how far one can automate communication.

## **Limits to automation**

Command must take responsibility for all actions taken, highest priority being given to

those which are life-threatening: this is the point of a Command and Control system. In some cases prior authority may be given for an automatic response to specific events, e.g. point defence, jamming ploys, but these must operate in a strictly limited domain and under the simplest of rules in order to avoid unpredictable behaviour.

The ability of humans to learn and solve problems is unmatched by any machine technique. Also, the ability of humans to 'get into the mind of an enemy' i.e. intuitive reasoning, is a uniquely human characteristic. These abilities must be recognised as most important in the unpredictable scenarios of modern warfare and must not be inhibited by any automated support functions.

The element of surprise, often by the deployment of new or 'crazy' tactics, has been crucial in any number of celebrated military victories, e.g. Nelson's defeat of the French at Trafalgar, Napoleon's defeat of the Austrians at Austerlitz. It is extremely unlikely that a KBS, essentially a conservative doctrine-based system, would recommend the tactics employed to secure these victories. The converse of this is that a tactical response encoded in a KBS could give an advantage to an enemy who gained access to it.

### **The role of the expert**

KBS require expertise which is in very short supply and distributed among a number of experts. Unless some way is found to retain this expertise then it may happen that knowledge will be lost and systems of the future become less capable.

Expertise which is regularly applied and for which performance metrics can be regularly monitored is valid to acquire for a KBS. In Command and Control however, much of the 'expert' knowledge is rarely put into practice and is consequently very difficult to validate; this could explain why experts often differ or it could indicate that their knowledge has a subjective component. Such knowledge would be dangerous to use for a KBS and will ultimately limit the scope of machine support - though this is a proper limitation in the sense that the strength of machines is in objective reasoning and that subjective reasoning is the province of humans.

Some expert knowledge can be very hazardous to codify in a KBS. An example here is that in the standard RN surface-ship training at Portland, operators knew that on Thursdays the air threat came from the west and so they would assume that any object approaching from the west at high speed was an enemy without any further evidence. DFTDS does not have this knowledge, which is based on experience, and although it could be incorporated by reference to the time, day of the week and ship's position, the dangers of attempting to incorporate it are obvious. Note that this is just the sort of conditions where a neural net approach to data fusion could yield similarly dangerous results, with less obvious visibility of trouble to come.

### **Trust**

A problem with using a KBS to fuse data and present an assessed picture, is that for the operator to accept this highest level picture implies complete trust on his part in the data fusion process which has created it. Will, or should, humans totally trust a computer?

Assuming that the answer to that is 'no', a KBS must have some way of explaining its reasoning process to those who use its output. Here is a significant bottleneck in the Human Computer Interface (HCI). Even using modern colour graphics to convey explanations of the system operation to the users there is so much information and reasoning being performed by the machine in real-time that a human cannot keep up. It is difficult to present all the reasoning behind a hypothesis, and particularly difficult to represent levels of confidence, to an operator, and actually some of it requires a depth of knowledge beyond that of the average operator.

Interestingly, our experience at sea is that explanations are not sought as much as anticipated, partly because obtaining explanations can be too slow for fast moving situations, partly because operators sometimes find it difficult to understand the explanation, and partly as 'It's obvious when it's wrong, so I don't need an explanation'. There is certainly danger in users simply disbelieving the data before them. None-the-less, an explanation facility is considered by users as an essential feature and has proven invaluable in system development.

## Procurement Policy

The current approach to defence procurement does not seem to have had much success when complex software is involved. Although cost can be controlled, time-scale and the ability of the system to meet operational requirements usually suffer. This situation will be exacerbated by attempting to introduce higher levels of automated support because these levels are much more sensitive to the operational environment. Our attempts to find KBS systems which have been formally procured have failed - the practice every time seems to be a series of prototypes and those that are successful require constant adaptation - certainly in complex problem domains.

The incremental approach used for building the DFTDS in fixed time and cost stages has worked well but it is poorly matched to current military procurement strategies. Unless knowledge captured in this way can be maintained and enhanced on a continuous basis, and exploited as widely as possible then the procurement process will place an artificial limit on the use of technology.

## Summary

DFTDS is of sufficient scale to provide realistic lessons for future RN Command and Control procurements. This is what is expected of a technology demonstrator programme, but is not easy to achieve in the Command and Control domain because of the software complexity involved.

In brief, the achievements of the programme so far are:

- By adapting KBS techniques we have been able to build a system which runs in real-time and with sufficient capacity to handle real data volumes obtained at sea.
- We have shown the potential value of using commercial off the shelf hardware and software for reduced acquisition and ownership costs.
- Incremental development with user involvement and feedback from trials has been a great success.
- We have established a baseline of data fusion performance with existing inputs and are now in the process of predicting, by demonstration, what level of performance can be achieved with sensor improvements.

- The display symbology and HCI generally have been a great success, providing operators with an instant grasp of the tactical situation with a single glance at the screen.
- We have established a large amount of detailed knowledge concerning the capabilities and limitations of the technology and shipborne environment.

The following lessons have been learned:

- KBS technology allows complex knowledge to be mechanised but that knowledge is fixed once it has been engineered. Adaptive techniques are becoming available but it is not clear how to use them in a complex Command and Control domain without a system learning inappropriately.
- Some knowledge is subjective and should not be mechanised - the boundary of subjectivity is not always easy to define.
- The human computer interface can be a bottleneck in terms of machines being able to understand normal human communication.
- Some knowledge is difficult to acquire and validate owing to its rarity and infrequent use.
- Automated support functions rely on quality controlled data inputs. These are not available from current sensor/communications systems.
- There is more information than a human can keep pace with - automation adds extra layers to the data available all of which may be needed to provide users with the confidence they need to be responsible for actions.

## Future developments

Much work remains to be done to further evaluate data fusion for tactical picture compilation and to develop automated support for situation assessment and resource allocation.

Data fusion at the force level, as well as the single ship level, will be studied in our on-going research programme.

DFTDS in its open systems/open standards form (now dubbed CMISE - the Combat Management Integration Support Environment) will provide a core component of DERA's programme of technology demonstration and

research to evaluate potential solutions to future combat system requirements. It will also play a vital role to de-risk the development of functional and non-functional requirements on which to base the procurement of future combat systems.

# Modeling and Monitoring the Crew

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## 1 Summary

The physiological state of the crew of the aircraft has been ignored in the development of Human-Electronic Crew systems. Environmental stresses such as acceleration, altitude, fatigue, and thermal load can challenge the physiological capability of the crew such that cognitive function is degraded or even eliminated as in the extreme case of Gz induced loss of consciousness. This paper describes both the development of first-principle and data driven models of the physiological and cognitive changes that occur in the pilot exposed to the tactical environment and the AI techniques under development for both monitoring and incorporating the physiological and cognitive state of the pilot into human-electronic crew systems. Such a capability will allow the optimization of the electronic component of the crew with respect to the physiological and neurological state of the pilot.

## 2 Introduction

In almost all discussions of human-electronic crew systems there has been little mention as to whether or not the human crew has the physiological "right stuff" - i.e., is the human crew member capable of functioning at an optimal level to interact with the electronic components of the system? To date the concept of predicting and/or monitoring the physiological capability and/or integrating the aircrew life support system into the human-electronic crew has been, with few exceptions [10, 18], been ignored.

Environmental stresses such as acceleration, altitude, and thermal load can challenge the physiological capability of the crew such that sensory and cognitive function is degraded as in the case of physical or mental fatigue or even eliminated, as in the case of Gz induced loss of consciousness.

Models of the crew can be developed from first principles and empirical data which can provide a state

representation of the pilot. Physiological (and cognitive) monitoring can be used to provide a real-time update of the pilot state model for both enhanced life support response and information for the electronic crew-member.

## 3 First Principle Models

Models of the various components of the human physiological system have been under development for a number of years [3, 21, 20, 17, 16, 6] with the majority of researchers modeling the cardiovascular, cerebrovascular, or pulmonary subsystems. The models have increased in complexity over the years as the computational capability to solve the large number of differential equations has also increased [19].

In spite of the increasing sophistication of these models there is general disappointment in that few experimentalists cite them, use them in their experimental design, or compare model results to experimental data. The use of large numbers of poorly known parameters places further doubt on the validity of the models. A major drawback to many of the models is the use of the electrical analog representation to describe the physiological systems. This can be misleading when nonlinear physical resistances and capacitances need to be included. In addition there is limited use of rigorous validation, verification, and sensitivity analysis techniques and almost no attempt to validate the consistency, stability, or the convergence of the numerical techniques used to solve the systems of differential equations.

The majority of the modeling effort has focused on clinical applications [19], and even in the cases where effort is directed towards acceleration [6, 16] or altitude stress, the focus has been on a single area such as the cardiovascular system or a subsystem such as the cerebrovascular system. Almost all of the models developed to date suffer from a number of inherent limitations in so far as their application to the development of advanced life support systems

is concerned. Due to the complex nature of the tactical environment most models are deficient in fully accounting for the uniqueness of this environment, the complex interactions between the various physiological systems, and the interactions between the physiology and the life support systems. For example, in a pilot exposed to complex negative and positive Gz stresses [2], wearing an anti-G suit, positive pressure breathing mask and jerkin, and performing an appropriate anti-G straining manoeuvre, there will be an interaction among the dynamics of the cerebrovascular system, neuronal and hormonal control systems, muscle function, respiratory mechanics, respiratory gas exchange, and the dynamics of the G-suit and breathing system pressurization systems.

None of the models developed to date can even incorporate or model the anti-G straining manoeuvre (AGSM) which includes isometric contraction of the limb muscles and exhalation against a closed glottis. Some models have incorporated positive pressure breathing and anti-G suits [6]. The current models do not account for the effects of fatigue on venous and arterial compliance, for the decrease in systemic blood volume due to tissue edema with prolonged +Gz and PPB exposure, or for the effects of changes in  $P_aO_2$  and  $P_aCO_2$  on the efficacy of the anti-G straining manoeuvre.

A recent paper by Melchior *et al.* [15] outlined a comprehensive framework for future efforts in the modelling of the entire cardiovascular system, especially with respect to acceleration stress. In order to address the deficiencies of the current models for more global problems such that they will be useful in the investigation of the physiological consequences of environmental stresses, and provide a useful tool for the development of aircrew life support systems, a number of general and specific enhancements are required:

- Incorporate the effects of acceleration, altitude, thermal, exercise, and protective equipment induced stresses.
- Incorporate the effects of positive pressure breathing (PPB) on chest wall dynamics, breathing patterns, gas exchange, neuronal control of breathing, lung baroreceptors, ventilation/perfusion ratios, and blood chemistry.
- Incorporate sensitivity analysis techniques in the modelling software.
- Integrate the cardiovascular, cardiopulmonary, cerebrovascular, pulmonary, gas exchange, and

life support systems models.

- Incorporate thermal regulatory and exercise responses.
- Integrate lumped parameter models and time/spatial computational fluid dynamics models of the pressure-flow distributions in the heart and blood vessels.
- Incorporate the effects of changes in  $P_aO_2$  and  $P_aCO_2$  levels on local vascular compliance, local blood flow regulation, and baroreceptor and chemoreceptor function.
- Incorporate the effects of lactate, potassium, and pH on vascular compliance, local neurotransmitter release, and neurotransmitter sensitivity.
- Include the neuronal and hormonal control of vascular compliance, muscle contraction, recruitment of the vascular beds (systemic and cerebral), heart rate, heart contractility, respiratory rate, airway diameter, and heart chamber compliance.
- Include models of the efficacy of PPB and G suit pressure application to the thoracic compartment and abdominal/leg vascular system.
- Develop sub-models for intra- and inter-muscular blood vessels, including the effects of muscle and organ pressure/volume compliances and vascular leakage.
- Incorporate models of muscle function including the development of muscle tissue pressure.
- Develop fluid dynamical models of anti-G suits, PPB garments, and as well as the mechanical and fluid dynamic characteristics of anti-G valves and breathing regulators.

### 3.1 Cerebral perfusion

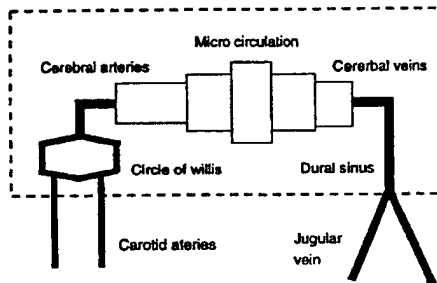
Given the overall complexity of the modeling problem, our laboratory has focused on a rigorous 1-D finite element model of the pressures and flows in the heart and systemic circulation and a lumped parameter model of the cerebral perfusion of the head to address a specific problem in acceleration physiology - why does Gz-induced loss of consciousness (GLOC) occur.

The perfusion of the brain is dependent on both the perfusion pressure, i.e., the difference between the arterial and venous pressures, and the resistance to



perfusion. The resistance of cerebral perfusion is under tight control in the brain though there is extensive debate as to the importance of metabolic, myogenic, or neuronal mechanisms in regulating flow. Beginning with Akesson [1] and Henry *et al.* [7], it has been implicitly acknowledged that the Gz-induced hydrostatic gradient should not affect cerebral blood flow and induce GLOC, due to the protection from the siphon effect.

A simple, steady state, lumped-parameter model of cerebral perfusion incorporating well-established parameters of the structure of the cerebral blood vessels was developed (Figure 1).



**Figure 1.** Lumped parameter model of the cerebrovascular system used to determine the vascular segment responsible for restricting cerebral blood flow during exposure to +Gz.

The governing equations for the model are:

- Momentum

$$(P_1 + \rho g H_1) - (P_2 + \rho g H_2) = \frac{8\rho\pi\mu L}{A^2} Q$$

- Continuity

$$UA = Q = \text{const}$$

- Tube Law of the blood vessels

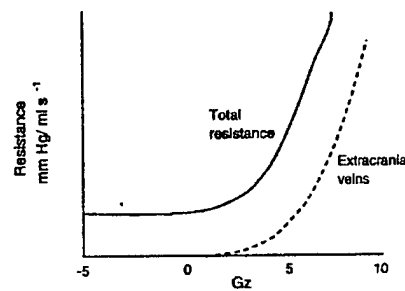
$$P - P_e = F(A)$$

- Conservation of volume

$$V_{\text{cranial}} = 0$$

This model demonstrated that the primary vessel responsible for regulating blood flow during positive Gz exposure is the jugular vein and that collapse of the jugular vein is responsible for the

loss of consciousness during high Gz (Figure 2).



**Figure 2.** Contribution of extracranial veins to blood flow resistance in the head during -Gz and +Gz exposure.

## 4 Empirical Models

Though the use of first-principle models of the physiology and life support systems can be useful for specific questions, the need to identify the extensive set of system parameters still makes it difficult to develop accurate models of the entire pilot/life support system. A more common approach is the development of empirical models of the total system response to the various environmental stresses. With the use of both linear and non-linear analysis techniques, parsimonious models of the complex responses of the pilot to environmental stress can be developed that are rich enough to characterize the state of the pilot.

Models range from simple time independent relations of the cerebral blood flow as a function of Gz, to complex linear (transfer function), non-linear autoregressive moving-average (NARMAX) models of the cardiovascular responses [13, 14], and neural nets. A typical NARMAX model of the cerebral blood flow response to Gz could be given as:

$$\begin{aligned} CBF(t) = & a_0 CBF(t-1) + a_1 CBF(t-1) \\ & + \dots + a_n CBF(t-n) + b_1 G_z(t) \\ & + b_2 G_z(t-2) + \dots + b_n G_z(t-n) \\ & + c_0 CBF(t-1) G_z(t) \\ & + \text{higher order terms.} \end{aligned}$$

Given sufficient data from sufficient pilots over a wide range of environmental stresses, a comprehensive model of the pilot's response can be developed. This is still insufficient to characterize the pilot through-

out the mission.

## 5 Pilot monitoring

No *a priori* modeling of any physiological system can account for all of the combined physical stresses that a pilot will be exposed to in the tactical environment. A more viable approach is to have the most accurate state representation of the nominal pilot (based on first principle or empirical models) stored in the aircraft systems. Monitoring of the pilot's physiological and cognitive responses can be used to modify the state model on a second by second basis. This information can be passed to both the life support hardware and the electronic crew member [4]. The electronic crew member in turn can pass information to the life support system to aid that system in providing optimal protection given the past, current, and future state of the mission.

A wide range of physiological signals can be collected on the cardiovascular, neurological, and thermal state of the pilot in real-time. Of primary interest with respect to acceleration and altitude stress is monitoring the delivery of oxygenated blood to the brain. Direct measures of cerebral blood flow and oxygen levels in brain tissue would be ideal. There has been significant developments in near-infrared spectroscopy techniques that do have the potential for non-invasive monitoring of the amount of oxygenated hemoglobin in the brain as well as the redox state of the cytochrome  $aa_3$  molecule of the respiratory chain. Cerebral blood flow monitoring in the cockpit environment is not yet possible but the use of phased-array doppler probes and advanced signal processing techniques may overcome some of the difficulties in monitoring in the high Gz environment. A surrogate measure of oxygen delivery can be determined from monitoring hypoxia induced changes in electroencephalographic (EEG) signals, though it is difficult to detect changes in either time or frequency dependent characteristics of the EEG signal during mild or moderate hypoxia.

An accurate assessment of thermal stress is one of the most difficult to obtain (possible with the use of rectal probes but not acceptable to pilots!). As the measurement of thermal stress demonstrates, the most difficult aspect of monitoring is the development of robust, accurate inexpensive sensor technologies that are both transparent and acceptable to the pilot during pre-flight preparation and in the cockpit. The second problem is the development of analog signal conditioning and digital signal processing techniques that can deliver an accurate assess-

ment of the physiological parameters in the electrical noisy and artifact generating environment of the cockpit.

One area that has shown significant progress has been the development of signal processing algorithms that correlate changes in EEG or eye-movement with cognitive states and performance using wavelet, time frequency-spectral, and neural net signal processing technologies [22, 12, 11]. Accurate detection and correlation with performance decrements ranging from mild to severe (i.e. GLOC) may be possible. These techniques combined with advances in relating brain models and cognitive function improve the probability that EEG monitoring can be a viable technology in the cockpit. The largest barrier to cockpit EEG has and will remain the development of sensors for incorporation into the helmet.

Techniques for monitoring the physical fatigue levels have matured and now include metrics extracted from cardiovascular parameters [5, 8], the electromyogram (EMG) [9], and the breathing patterns of the pilot.

## 6 Integration into the Electronic Crewmember

This paper argues that systems for both modeling and monitoring the pilot and the life support system should be integrated into the electronic crewmember (Figure 3) in essence developing what Dr. Mark Darrah of Gentex Corporation described as the *Human Avionics System*. Development of an updated model of the physiological and cognitive state incorporating data fusion techniques and other AI technologies such as neural networks and fuzzy logic is needed to provide a composite representation of the human crew component to the electronic component

Combining first principle and empirical models with real-time monitoring, and integrating this data into a state model of the pilot can optimize both the life support systems of the aircraft as well as provide information to the electronic crew component.

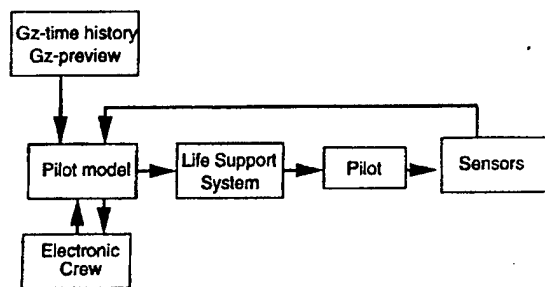


Figure 3. *Schematic of real-time feedback control of an adaptive life support system providing Gz protection. The system is constantly updating and refining the state model of the pilot and providing pilot status information to the electronic crew member. The initial pilot state is based on first-principle and/or empirical models. For subsequent missions a new pilot model and state estimator is stored.*

## 7 Conclusions

Any system involving human-electronic crew interaction must be capable of providing a real-time model of the physiological and cognitive state of the pilot, the ability to undertake trend analysis on that state, and predict the state for the future course of the mission.

The aircrew life support system must be an integral part of the human-electronic crew system, both to maximize human crew performance and provide crew state information to the electronic crew component.

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## GROUP DISCUSSIONS

### 1. INTRODUCTION

Group Discussions were convened during the final two days of the meeting for the purpose of developing understanding on new issues. Participants were divided into multi-disciplinary groups, each with a designated leader, and with a set of pre-selected issues to consider and to evaluate. This section summarizes reports of the group leaders to final Plenary Session of the meeting. Also included are copies of cartoons drawn by Mike Busbridge to illustrate progress and status in the area, since the first meeting in 1988.

### 2. PROCEDURE

The programme sought to make the workshop productive by developing a shared understanding on new issues. Accordingly, the aim of the Group Discussions was to enable the emergent issues to be addressed in a systematic, and yet informal manner, with the widest participation from all attendees. In order to facilitate this process, all participants were invited to begin to identify and analyse key issues from the start of the meeting. The aim was to develop personal understanding of other participants' views and opinions, through both formal and informal discussion (i.e. in the bar), or whenever seemed appropriate. Ideally, these discussions would be taken forward throughout the meeting, and not held to the end, when the organised Group Discussions took place. Whilst interested in the views of individuals, the organisers sought analyses which synthesised the range of perspectives and positions that were available at this multi-national, multi-disciplinary meeting.

#### 2.1 Identification of Issues

Participants were particularly encouraged to address areas of uncertainty, or problems requiring resolution. The organisers were interested in arguments rather than statements of individual's positions. It was briefed that issues should be approached in the form of questions using the simple imperatives *Why? What? Which? How? Who? Where? and When?* Also, it was considered helpful to frame issues in terms of contrasting positions, such as "A or B?" or "C versus D?"

#### 2.2 Recording of Issues

Participants were provided with two forms. These sought to help capture analysis of issues. The first form was for reporting the order of priority of the important issues identified by the group. The second form was for recording justification information for high priority issues. This required information on the following:

- ☐ Implications of the issue for Human-Electronic Crew (H-EC) teamwork;
- ☐ Factors affecting the issue;
- ☐ Other relevant issues;
- ☐ Relevant knowledge i.e. lessons learnt, current practice, methods and techniques;
- ☐ Potential directions i.e. requirements, alternatives, choices, priorities, and cost/benefits.

The forms were used to capture the results of the Group Discussions and to record individual analyses. Acetates of the forms were used as overheads to assist Group Leaders' summary presentations in the final Plenary Session. The reports of the group discussions provided in this section are based on the content of the leaders' briefings.

### **3. INITIAL ISSUES**

The meeting Call Notice identified a series of issues relevant to Human-Electronic Crew teamwork. Participants were encouraged to consider these issues, and others that emerged during the paper presentations, in particular those arising from the Keynote Address . It was suggested that issues that had arisen at previous meetings might still be relevant. During the meeting, a list of emerging issues was collated and displayed for consideration. Participants were encouraged to add to this list as the meeting proceeded. The following is a list of the initial issues presented for consideration by the participants at the 1997 meeting, including issues raised in 1994.

#### **3.1 1997 Theme Issues: The Right Stuff**

- ☐ What are the core qualities that the Electronic Crewmember must possess?
- ☐ How does one estimate the amount of software code involved?
- ☐ What are the key software modules?
- ☐ What is necessary to ensure the modules function symbiotically?
- ☐ What is sufficient functionality within the Electronic Crewmember to satisfy the human operator requirements?

#### **3.2 Additional 1997 Issues**

The following issues, statements and questions were raised by individual participants for consideration in advance of the meeting:

##### **3.2.1 Issues**

- ☐ Are common architectures possible?
- ☐ Is knowledge re-use possible across a wide area?
- ☐ Are conventional validation methods applicable to decision support?

##### **3.2.2 Statements on Certification: Agree or disagree?**

- ☐ Achieved design quality is the degree of adherence to design requirements.
- ☐ Certification activities should be related to the individual stages of the relevant life cycle.
- ☐ Certification is a progressive activity conducted throughout both the software and system life cycles
- ☐ Certification is the process of checking the justification of design choices rather than of the design rationale per se.
- ☐ Design is the traceable maintenance of relevant documentation: such documentation is the design.
- ☐ Formal engineering methods show a greater utility to Knowledge Based System engineering than the use of like methods in software engineering.
- ☐ Provided the software process model can be understood, the software can be certified.
- ☐ Software correctness (degree of programmed validity of rules, knowledge etc.) is equivalent to safety - the designed degree of correctness being made appropriate to known requirements of the software's application domain.
- ☐ Verification is concerned with checks to promote good design practice; Validation is concerned with checks concerned with interpretations of fitness for purpose.

### **3.2.3 Questions**

- ☐ User-centred or use-centred design?
- ☐ Adaptive systems or adaptive interfaces?
- ☐ Adaptive or adaptable.....?
- ☐ Function allocation or integration?
- ☐ Physical or logical specification?
- ☐ Specified or emergent system properties?
- ☐ Dependency versus autonomy?
- ☐ Feedback or feedforward control?

### **3.3 1994 Theme Issues: Can We Trust the Team?**

- ☐ Do current development activities address the teaming issues?
- ☐ Are there some types or categories of decisions or actions that the Human-Electronic Team should never be trusted with?
- ☐ What oversight checks should be placed on the Team?
- ☐ How does the Team communicate with the higher authorities?
- ☐ Are there other issues besides teaming which are crucial to the operational application of the Electronic Crewmember concept?

### **3.4 1994 Keynote Issues:**

- ☐ Who should be the team leader - the mission computer or the human?
- ☐ What types of teams should the system emulate?
- ☐ How do we ensure that the team samples we experiment on are representative?
- ☐ What human characteristics should we allow for in our team?
- ☐ How many humans should there be in the aircraft?
- ☐ How much should the team members trust each other?

### **3.5 1994 High Priority Emergent Issues:**

- ☐ To implement an EC, shouldn't we adopt a stepped approach to improve existing and new cockpit modalities?
- ☐ Can we justify not sharing technology?
- ☐ Without models of human decision making, can we build adaptive intelligent systems?
- ☐ What authority structures and EC roles should there be in a multi-user environment?
- ☐ How do we measure and predict success?
- ☐ How do we, as a community, demonstrate the benefits of EC?
- ☐ How do we provide guidelines on design and test procedures for the team as a unit?
- ☐ How do we provide a design framework to include the role of the operator?
- ☐ How do we ensure that the H-EC team functions when faced with the unpredicted mission?
- ☐ How do we know that the design is based on the right operational tasks and context?
- ☐ What are the barriers to our problems with designing an effective pilot/EC interface, and how do we get around them?
- ☐ Where are we going?
- ☐ What are the stages?
- ☐ What is the standard?
- ☐ How much interoperability?
- ☐ How do we employ aiding in design?
- ☐ How do we achieve effective Pilot Vehicle Interface implementation?

- ❑ Should we start slowly and incrementally?
- ❑ Why has there been no development in EC in the last 4 years?
- ❑ How do we select representative samples of humans for use in H-E crew research and as a model on which to build systems?
- ❑ What are the teams and their rigorous definitions?
- ❑ What are the objective design and development criteria?
- ❑ How would an EC be flight and combat certified?
- ❑ How does one ensure that information of the highest priority is delivered to the pilot soon enough to make a difference to mission effectiveness and survivability?

### 3.6 Earlier Themes:

- ❑ 1990: Is the Team Maturing?
- ❑ 1988: Can they Work Together?

## 4. GROUP DISCUSSIONS REPORTS

### 4.1 Group 1

#### *Membership:*

Tim Barry  
 Frank Hoeppe  
 Tom Metzler  
 Chris Miller  
 Plus notes from Thierry Joubert

#### *Priority Issues:*

1. How do we provide cost/ benefits analysis and justification for ECs? It was noted that the 2<sup>nd</sup> and 3<sup>rd</sup> listed 1997 Initial Issues were both cost/benefit or money issues.
  - ❑ This requires consideration of 'What will sell?' and of 'How can we know?' On 'what to sell?', if not the dream (i.e. now), we should consider how can we sell pieces towards the dream? The question was posed: 'Can EC sell relative to more traditional approaches.' It was noted that costs are accurate measures, whereas benefits differ from domain to domain. It might be possible to sell EC on its own, or on the coat tails of something else e.g. free flight. It was also noted that integration can save money, but only to the integrator or customer.
2. What practical steps are required toward achieving real world ECs (evolution)?
  - ❑ It was noted that an evolutionary approach implies the provision of simple, limited functionality. To do more may be limiting to acceptance. But it was in breadth of integration where the big payoff resided. The required steps (and functionality) would differ across domains and missions. It was also necessary to understand the path toward the goal. For future direction, it would be necessary to consider the difference, if any, between a simple decision aid and a baby EC.
3. How do we ensure that steps are compatible with the EC dream for system integration, and ultimately system certification?
  - ❑ To ensure that steps are on the path to the goal, we need to understand the growth path, and we may need to give up the EC name. Generic EC architectures can help this



progression. Human Machine Interface and functionality may need to be considered as separable issues. Integration of components was the *sine qua non* of EC. Again, integration can save money, but only to the integrator or customer. It was relevant to consider shared knowledge bases, and shared task and world models. Future work should include the sharing of requirement specifications for EC. There was a need to 'black box' the specification/requirement for disparate people to work forward. But the Pilot's Associate did this! We need to ask why it was not successful?

4. How do we determine the required levels of authority? There was considered to be a need to overcome the 'Pilot in control' barrier. The required analysis needed to be conducted across application domains and across the mission.

With regard to the 1<sup>st</sup> Initial Issue, concerning the required core capabilities of EC, it was noted that the core functionality was that of a 'back-seater' providing information filtering and prioritisation.

On this issue, Thierry Joubert noted that in the Co-pilot Electronique rules, the first was to help the pilot to anticipate, and the second was that the EC must know and respect it's own limits (i.e. real intelligence). So, the EC must be robust. Good models were needed for the domains that produce problems (e.g. threats, failures). The design of the Man Machine Interface should be carefully done with a good cognitive approach. He believed that a multi-agent supervised architecture could be standardised. EC's way of thinking should 'mimic' some particular human pilot, providing a natural dialogue that avoided surprises. For future directions, Thierry Joubert recommended work on "any time algorithms" for real time robustness, and on "high fidelity simulation" for combat robustness.

## 4.2 Group 2

### *Membership:*

Simon Goss  
John Reising  
Gordon Semple  
Joe VonHolle  
Dave Williamson  
Robert Zanconato  
(aided by Asimov, Lucas, Orwell)

### *Priority Issues:*

1. Is the mission the proper analytic focus, rather than task analysis?
  - ❑ An implication of this statement was considered to be that analysis of H-EC Teamwork required additional categorisation (boxes). Psychological analysis was considered to be at the task level. The pilot's role was to give the mission a 'better spin'. Will the EC 'emerge' in the super-sub-systems?
  - ❑ Consideration of EC emergence was believed to have implications for the integration of intermediate steps, for synergy arising from a 'chunked' development, and for the overall steer of distributed development of an H-EC system. The possibility of implementation

'windows' for emerging functions was raised as an influencing factor affecting this issue, along with the requirements of 'plug and play' standards.

2. What is the required architecture for delivery?

- The possibility was raised that EC may be implemented in a wearable form, and as a retro-fit. Wearable computing was under development for foot-soldiers. Commercial portable devices were wearable. Issues arising from consideration of matching the brain to boxes, and standards of inter-connectionism were identified as related to the questions of delivery architecture.

3. What dynamic is needed to provide the required change in command?

With reference to the workshop lead issue/question about EC core qualities, it was noted that George Lucas had provided the following suggestions: *"Extend my sensors; follow my lead; do what I ask; cover my butt and give sensible suggestions which match the urgency of the moment...."* It was suggested that we should not allow EC to be viewed as "Big Brother", nor as a psycho-analyst. Rather, EC should be seen as a "kick-butt, ice water cool warrior".

### 4.3 Group 3

*Membership:*

Lt Andrew (Gadget) Davies

Dr Forster

Peter Gosling

Dave Harry

Howard Howells

Reiner Onken

*Priority Issues:*

1. How do we resolve the competing design constraints and requirements as drivers of system development?

- This issue was considered to have implications for the need for evolution or revolution in the H-EC Team; for whether to automate or assist; for the need for complete, robust, and flexible systems; and for the implications of technology driven solutions. It was thought that the issue was influenced by consideration of system architectures, proposed platforms, technology and cost. Standardisation was a related issue. Consideration was needed of knowledge of front line/operational requirements, comparison of different systems, and lessons learnt from the Pilot's Associate (PA) and Rotorcraft Pilot's Associate (RPA) programs. Future work should seek to maximise benefit from the cross-pollination of ideas arising from PA/RPA, Crew Assistant Military Aircraft (see paper 8), Copilote Electronique (see paper 7), etc.
- How do we determine the appropriate task allocation i.e. human/machine split or teamwork?
- This issue was considered to have H-EC Team implications for human-only responsibilities, for overlap of task support, for any unsupported tasks, and for dynamic changes dependent on temporal requirements. It was thought to be influenced by system trust, cost and training, certification requirements, and cognitive workload and mission complexity. The requirements of crew acceptance, system perceived conflicts, and

cooperation / teamwork provided related issues. Useful knowledge for determining the appropriate task structure arose from understanding about implemented and designed systems (e.g. RPA/PA), from the automation versus assistance debate, and from research on co-operative working.

2. What approach to H-EC system control?

- This was considered to have implications for the level of control required, the method of control, and the nature of the control loop. Cost and complexity were thought to be key factors influencing system control considerations. Crew training was a related issue. Lessons learnt from PA/RPA should be valuable. The way forward was to test and demonstrate control options to determine the R&D required.

3. Is the route to certification through standards?

4. What are the alternative methods to human emulation?

#### 4.4 Group 4

*Membership:*

David Barr  
George Brander  
Mike Busbridge  
Harmut H  
Gunter Kroh  
Iain MacLeod  
Tim Normanton

*Priority Issues:*

EC/Human teaming was identified as the key issue.

This has implications for the 7 Cs of teaming in the H-EC Team, namely:

- Cohesiveness
- Coordination
- Communication
- Control
- Concurrency
- Collaboration
- Cybernation

It also has implications for the 3 Ts, namely:

- Tactics,
- Training
- Technology

Factors influencing EC/Human teaming were differences between humans and machines, command style, and that only a human can be 'situationally aware'. Other related issues included reliability, quality, training and certification. Consideration should be given to the relevance of knowledge of training for teams and selection. Potential future directions for developing understanding included:

- ❑ How does the pilot configure or personalise the team?
- ❑ How to train teams?
- ❑ The need for a new type of pilot?

In an individual submission, George Brander identified EC/Human Teamwork as the key issue. He believed that the main implications were that EC must be commander of a crew of EC functions or modules. The pilot must delegate tasks, responsibilities and ways of reporting. George Brander advised that we must have a system configured to best suit the mission and the pilot; this involved training issues and certification. Influencing factors were that only the pilot could have situational awareness and anticipation (feed-forward?). EC functions must be reliable, predictable, but also adaptable by the pilot commander to serve his/her needs. A related issue was that symbiosis was the product of a good team. He considered that emergence was the problem of unwanted factors arising. He noted that mission rehearsal should be used to test tactics and EC responsibilities. For potential directions, George Brander identified architectural implications as important i.e. "How does the pilot configure or personalise his team?" He noted that this question was about more than just configuring the displays. Research was needed on how to train teams (i.e. individual skills versus team skills). On certification, he advised that this should be of the platform (e.g. aircraft), in the way that the Navy assesses a ship's capability.

Mike Busbridge also submitted separate notes indicating a priority flow from the team, to the pilot-in-charge, to delegation, with trust and training as related issues. He advised that the EC must have the ability to handle its delegated tasks autonomously, in a timely manner. Also, EC must have knowledge of its limitations to pass over the problem when it gets beyond its competence. Mike Busbridge suggested that it would be useful to know what task(s) it (EC) is competent in now, perhaps as a list. He noted that the most useful tasks are the most difficult to implement. For future work, Mike Busbridge described a team trainer, with a focus for the EC on the 7 Cs (Group 4 issues), and a focus for the pilot on individual characteristics.

## 4.5 Group 5

### *Membership:*

Floyd Glenn  
Karmen Guevara  
Rod King  
Ron Small

### *Priority Issues:*

1. How to provide a multi-disciplinary approach?
  - ❑ The need for a multi-disciplinary approach in developing the H-EC Team was thought to require a continual re-visiting of requirements, using a holistic perspective. Key factors influencing the provision of a multi-disciplinary approach were considered to be organisational and academic segregation, and unpredictability in the use of the system. Another related issue was the approach taken to prototyping.
2. How to separate function and use?

- ❑ This issue was believed to have implications for unused and unusable functionality in the H-EC team. A key factor was the separation of the user from the developer, and from Human Computer Interface specialists.
- 3. When to provide advisory versus supervisory support?
- 4. How to combine evidence?

#### 4.6 Group 6

##### *Membership:*

Ulf Berggrund

Gert Dorfel

Dieter Scheithauer

H Vaic

##### *Priority Issues:*

1. For functional requirements analysis:
  - ❑ How to classify mission tasks and pilot behaviour?
  - ❑ What constitutes flexibility for the EC?
  - ❑ What safety classification?
2. For the route to certification:
  - ❑ What traceable and adaptable methods and tools from other technologies can be used in certification?
  - ❑ What new methods can be used for compliance demonstration for the remaining tasks?
  - ❑ What is the feasibility and cost effectiveness of these new technologies?
  - ❑ How to start to invent these methods and tools?
3. For reusability:
  - ❑ How to provide a general classification of appropriate means to accomplish a certain task category?
  - ❑ How to get a common understanding of a modular system architecture.

The primary issue - functional requirements analysis – was considered to have implications for the effectiveness of H-EC Teamwork, particularly with regard to the following:

- ❑ mission accomplishment,
- ❑ safety, and
- ❑ user acceptance (feel good factor).

The key factors influencing functional requirements analysis were considered to be as follows:

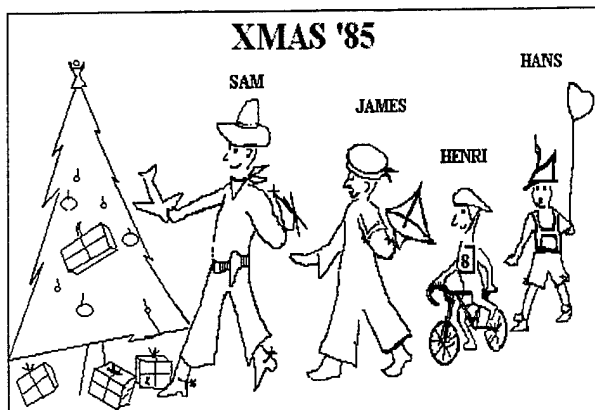
- ❑ the mission tasks,
- ❑ follow-on or new (from scratch) system development, and
- ❑ the required, allowable reaction time.

Other relevant issues in functional requirements analysis arose from consideration of the requirements for system analysis, cognitive task analysis, and organisation analysis.

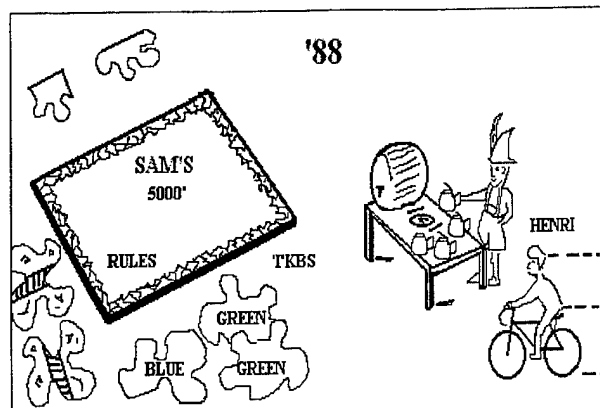
Knowledge that was considered to be relevant for functional requirements analysis included:

- ❑ understanding and classification of pilot behaviour
- ❑ understanding of flexibility, and
- ❑ classification of mission tasks.

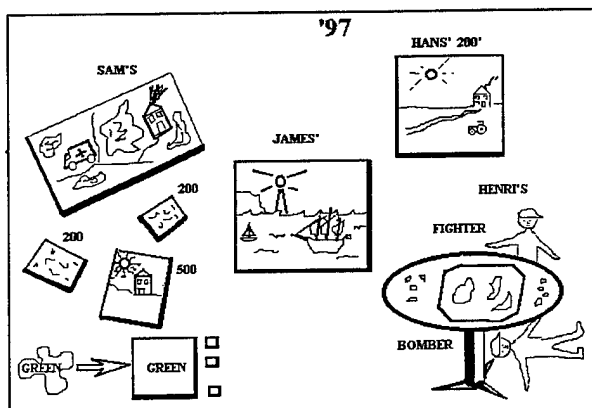
Potential directions identified for future work included the classification of tasks and pilot behaviour especially with regard to the requirements of testing and evaluation.



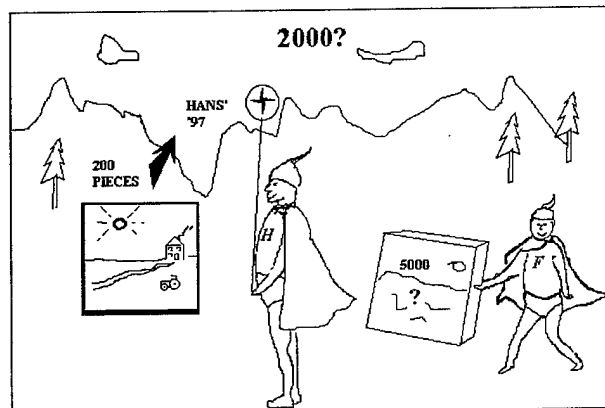
1. At Christmas 1985, Sam arrives first to collect his gift, proudly bearing an aeroplane, with a helicopter held discretely behind his back. James comes empty handed, but with a boat also held out of sight. Henri arrives on his bike. Hans arrives hopefully. The presents are all puzzles. But there are no pictures to guide them.



2. In 1988, Sam demonstrates progress with his big puzzle. He has put it together without the aid of a picture. With the help of some simple rules, the corners and sides are done. But the rest are only roughly sorted. He thinks he may need some more 'know-how' help to put them in place. Hans is in festive mood, enthusiastically assisted by James. They have both made good progress with their puzzles. Henri is seen to be dashing about on his bike.



3. By 1997, Sam has decided that he wants his picture to be a land battle. He has found some parts that seem to work, but they don't fit together. James proudly presents his completed puzzle. It is, not surprisingly, a naval scene. Hans lets us see his simple solution; it's a peaceful, civilian scene. Henri is working on two concurrent solutions to his puzzle. One is a bomber. The other is a fighter aircraft.



4. Looking forward, with 2000 foresight, nothing is certain. But, Hans, under a new pennant, confidently expects to be flying his simple, achievable solution. He rightly deserves a feather in his cap, and the title Super-Hans. Henri, also mit plume, offers the prospect of a new, big puzzle to solve. But he has not yet revealed his picture.